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RESEARCH PAPER

Dynamic Environmental Policy Design and ESG Performance Amid Market Competition and Adaptive Cannibalization Strategy

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Abstract

The global transition to sustainability places firms at a strategic crossroads, compelling them to balance profitability with Environmental, Social, and Governance (ESG) performance. This study confronts a critical challenge within this transition: the risk of internal cannibalization, where a firm's new green products erode the market for its conventional offerings. We introduce a novel two-phase, game-theoretic framework to analyze the dynamic interactions between duopolistic firms-an incumbent and a challenger-and a government regulator. Our analysis reveals that cannibalization is not an inevitable market force but an *endogenous strategic variable* that can be managed. We demonstrate that while calibrated policy support is crucial for catalyzing eco-innovation, overly aggressive interventions can paradoxically trigger a "crowding-out" effect, stifling private R&D incentives. The results show that the optimal path to aligning profitability with sustainability lies in a strategic dual-channel portfolio, where adaptive pricing transforms cannibalization from a systemic risk into a market capture mechanism. This research offers quantifiable policy thresholds to guide regulators and provides actionable strategies for corporate leaders to secure a competitive advantage in the green economy.

Keywords:
Green Product Development (GPD), Environmental, Social, and Governance (ESG), Market Competition, Cannibalization Strategy, Game Theory, Optimal Policy Thresholds.

1 Introduction

Framing the Modern Sustainability-Profitability Nexus: The contemporary business landscape is defined by an intensifying dual mandate: the relentless pursuit of financial profitability interwoven with mounting societal and investor-driven demands for superior ESG performance. Within this paradigm, Green Product Development (GPD) has evolved from a niche corporate social responsibility initiative into a fundamental pillar of strategic competitiveness. Firms are now compelled to navigate a complex frontier, balancing the immediate costs of green R&D against the long-term benefits of enhanced brand equity and sustainable market dominance (Badu et al., 2025; Boffardi et al., 2025).

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The urgency of this challenge is underscored by mounting global evidence. Green product markets have expanded at compound annual growth rates exceeding 15% in sectors such as electric vehicles and energy-efficient appliances, driven by tightening regulatory regimes (Jaffe et al., 2002; Wang et al., 2023) and evolving sustainability standards (Kneller & Manderson, 2012). However, this rapid expansion has simultaneously intensified competitive pressures, compelling established incumbents to invest heavily in green R&D while managing the risk that new eco-friendly offerings erode the profitability of existing conventional product lines (Brucal & Roberts, 2019; Elrod & Malik, 2017). The strategic complexity of this transition is further amplified by the need to respond to evolving consumer environmental awareness and competitive positioning strategies (Akan et al., 2022; Wagner et al., 2023).

Despite the growing body of literature on green product development, environmental policy design, and competitive market dynamics, a critical gap persists: no existing model simultaneously captures (1) the strategic interplay between a multi-product incumbent managing internal cannibalization and a green-only challenger, (2) the dynamic two-phase green market entry process, and (3) the government's Stackelberg leadership role in optimizing environmental policy under full awareness of firms' strategic responses. The present study fills this gap by developing a three-stage backward-induction game-theoretic model that endogenizes all three dimensions.

This corporate transformation is mirrored in the policy landscape. Governments worldwide are deploying an increasingly sophisticated mix of subsidies, green infrastructure investments, and performance-based incentives to accelerate the transition. However, the effective design of these policies presents a profound governance challenge. A central dilemma lies in architecting interventions-such as subsidies or infrastructure investments-that incentivize genuine eco-innovation without distorting market competition or fostering corporate dependency.

A critical, yet frequently underestimated, challenge for established firms is the phenomenon of self-cannibalization. The launch of a new, sustainable product line inherently risks eroding the revenue base of a firm's existing, conventional-and often highly profitable-portfolio. The automotive sector provides a classic illustration. Ford's introduction of its eco-friendly Focus, while successful, simultaneously cannibalized sales of its conventional Fiesta (Pope, 2012). In stark contrast, Hyundai's strategic launch of the Ioniq line demonstrated masterful portfolio management; by carefully positioning the product and its pricing, the company captured new market share while preserving sales across its conventional lineup (WardsAuto, 2017).

This dichotomy powerfully illustrates that cannibalization is not an inevitable market force but an *endogenous strategic outcome*. It is a variable that can and must be managed. This study seeks to understand the dynamic interplay between competitive strategy, government policy, and cannibalization mitigation. We address three fundamental questions:

1. How do dynamic strategies (pricing, green investment) interact with the cannibalization-mitigation calculus for firms transitioning to a green-inclusive market?
2. What is the non-linear relationship between government intervention and private R&D, and how can optimal policy thresholds be derived to prevent a "crowding-out" effect?
3. By explicitly incorporating a cannibalization penalty into the incumbent's profit function, what new equilibrium insights emerge for managing dual-channel product portfolios?

To address these questions, we develop a two-phase Stackelberg game model. This framework analyzes the sequential strategic interactions between two competing firms (an incumbent and a challenger) and a market-shaping government, focusing on the dynamic co-design of GPD strategies and environmental policies. Our analysis provides crucial theoretical advancements for game-theoretic models of sustainability and delivers practical, data-driven insights for policy design and for corporate leaders tasked with navigating the high-stakes journey toward a sustainable and profitable future.

Despite the growing body of research on GPD, green innovation policy, and competitive

dynamics, a critical gap in the existing literature remains: no prior study simultaneously models the dynamic co-design of environmental policy instruments alongside firms' adaptive cannibalization strategies within a unified Stackelberg game-theoretic framework. Existing models either treat government policy as exogenous, ignore internal cannibalization dynamics, or analyze firms' green strategies in isolation from regulatory optimization. This study bridges that gap by integrating all three elements - government policy design, competitive green investment, and adaptive cannibalization management - into a single, tractable analytical framework, thereby generating new theoretical insights and actionable policy guidance.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and identifies the research gaps. Section 3 formulates the mathematical model. Section 4 presents the solution methodology and analytical results. Section 5 reports the numerical analyses and sensitivity results. Section 6 concludes with managerial implications and directions for future research.

2 Literature Review

The transition to a green economy is a multifaceted phenomenon shaped by forces at the firm, market, and policy levels. This review synthesizes key research streams to establish the theoretical bedrock for our study.

2.1 Strategic Foundations

GPD as a Cornerstone of ESG Performance: The modern conceptualization of GPD is deeply rooted in the broader framework of ESG performance. No longer a peripheral activity, GPD is now recognized as a primary driver of a firm's environmental "E" pillar, which is increasingly correlated with superior financial performance, innovation capacity, and long-term competitive advantage (Wu et al., 2025; Zhang et al., 2025). The theoretical impetus for this shift can be traced back to seminal concepts like the Porter Hypothesis, which posited that well-designed environmental regulations could spur innovation rather than merely impose costs (Porter & van der Linde, 1995). This idea was further enriched by Elkington (1997). lkington and Rowlands (1999) Triple Bottom Line framework, which institutionalized the integration of economic, social, and environmental considerations into a unified corporate objective, a perspective empirically supported by contemporary research. Well-designed environmental regulation stimulates firms to develop more cost-efficient production processes, generating competitive advantages that offset compliance costs (Porter & van der Linde, 1995). However, that foundational work did not explicitly model the competitive dynamics emerging when multiple firms simultaneously pursue GPD under government incentives, nor did it account for the strategic risk of internal product cannibalization. Elkington and Rowlands similarly provided a normative integration framework but stopped short of deriving quantitative models capable of identifying optimal policy thresholds under duopolistic competition; more recent empirical work has strengthened this connection (Mura et al., 2024).

The primary drivers of GPD are a confluence of "regulatory push" from governmental bodies and "market pull" from an increasingly environmentally conscious consumer base (Hojnik & Ruzzier, 2016). This dual pressure compels firms to innovate, but the path to successful GPD is fraught with strategic dilemmas. The necessity for robust quantitative models to navigate these challenges-optimizing pricing strategies, aligning with regulatory incentives, and forecasting technological trajectories-has become a central theme in the literature on sustainable transitions. Regulatory pressure is the single most consistent driver of eco-innovation (Hojnik & Ruzzier, 2016); crucially, however, that study did not develop formal models to quantify optimal policy intensity under competitive market conditions. Governance challenges in ensuring inclusive sustainability transitions have also been identified (Poto et al., 2025), yet

without addressing the competitive strategic responses of profit-maximizing firms in oligopolistic markets. These gaps collectively motivate the need for a game-theoretic model capable of simultaneously capturing regulatory incentives, competitive dynamics, and internal portfolio management decisions (Poto et al., 2025).

2.2 Cannibalization Theory and Competitive Dynamics in Green Markets

The introduction of a green product by an established firm with a conventional portfolio gives rise to a critical strategic challenge: self-cannibalization. This occurs when the new green product erodes the sales and market share of the firm's existing offerings, creating a zero-sum game within the firm's own portfolio (Amiri et al., 2026). This internal competition is often more intense and complex than external rivalry, especially in markets with high product substitutability and a strong consumer preference for sustainability.

Firms have developed sophisticated strategies to manage this endogenous risk. These include dynamic pricing and market segmentation, which aim to position the green product as a premium alternative or a distinct offering for a new consumer segment, thereby minimizing direct overlap (Akan et al., 2022; Wagner et al., 2023). In some cases, firms may even strategically discontinue highly polluting product lines to streamline their portfolio and enhance their ESG profile (Elrod & Malik, 2017). Recent research has expanded the scope of cannibalization theory, demonstrating its effects in driving price declines after the implementation of new efficiency standards (Brucal & Roberts, 2019) and its relevance in emerging business models like the sharing economy (André et al., 2024). Our own foundational work established the initial competitive framework for a duopoly, revealing that even with high consumer environmental awareness, market outcomes could be suboptimal if not managed strategically (Amiri et al., 2026). This body of work confirms that cannibalization is a central, dynamic variable in GPD strategy. Pricing and segmentation strategies can moderate cannibalization but focus on demand-side consumer behavior rather than supply-side strategic interactions between competing firms (Akan et al., 2022; Wagner et al., 2023). Efficiency standards trigger price reductions consistent with cannibalization dynamics (Brucal & Roberts, 2019), while cannibalization theory has also been extended to the sharing economy (André et al., 2024). Neither stream incorporated government policy instruments as strategic complements to the firm’s cannibalization mitigation decisions - a gap this study fills by endogenizing the cannibalization penalty within the incumbent’s profit function.

2.3 Environmental Policy Design

Shaping the Competitive Landscape: Government policy is arguably the most powerful external force shaping the GPD landscape. The arsenal of policy instruments is vast, ranging from demand-side interventions like green public procurement (Cao et al., 2025) to supply-side incentives like R&D subsidies and mandates for closed-loop supply chains (Das et al., 2025; Luo et al., 2024), though neither modeled the full three-party Stackelberg interaction between an incumbent multi-product firm, a green-only challenger, and a regulating government (Jaffe et al., 2002; Wang et al., 2023).

The interaction between policy and market competition is particularly nuanced. Competition can enhance the effectiveness of environmental policies in liberalized markets (Nesta et al., 2014), but competition alone may drive firms toward low-quality, incremental innovations rather than breakthrough technologies, necessitating targeted policies for the latter. Research in sustainable supply chain management has provided deep insights into how firms make pricing, greening, and transparency decisions in response to government subsidies and CSR pressures (Khosroshahi et al., 2021; Sana, 2020). Furthermore, scholars like (Taleizadeh & Heydarian, 2017)have developed sophisticated quantitative models to analyze pricing and coordination in supply chains with green products, highlighting the importance of aligning operational

decisions with policy incentives (Taleizadeh & Heydarian, 2017).

2.4 Synthesized Research Gaps and Core Contributions

Despite the rich body of work in these individual streams, a significant theoretical gap persists at their intersection. Current research inadequately models the concurrent and dynamic interplay between market competition, evolving government policy, and a firm's endogenous cannibalization-mitigation strategy within a multi-phase market evolution framework. Specifically:

- **Lack of Dynamic Modeling:** Prior studies, including foundational work that established the competitive dynamics in a static, single-phase setting (Amiri et al., 2026), predominantly examine these forces in isolation or without capturing the temporal evolution of an incumbent's strategic transition from a conventional to a dual-channel portfolio.
- **Absence of Quantifiable Policy Thresholds:** While the literature acknowledges that excessive intervention can be detrimental, there is a scarcity of theoretical models that rigorously quantify the **optimal policy thresholds** (e.g., maximum effective subsidy rates) beyond which a "crowding-out" effect on private R&D occurs.
- **Insufficient Integration of Cannibalization Risk:** Existing frameworks have not fully integrated the internal cannibalization effect directly into the incumbent's profit function as an *endogenous cost of transition*, a necessary step for accurately modeling the strategic trade-offs inherent in dual-channel pricing and investment decisions.

To bridge these crucial theoretical and practical gaps, this study makes three primary contributions:

1. **Development of a Dynamic Equilibrium Model:** We develop a novel two-phase Stackelberg game model that integrates duopolistic competition, policy interventions, and the endogenous cannibalization effect, capturing the temporal evolution of strategic equilibria from initial market entry to broader green transition.
2. **Advancement of Adaptive Cannibalization Mitigation Theory:** We advance cannibalization theory by endogenizing the self-cannibalization effect (CaE) within the incumbent firm's profit function (πF_1^2), providing a robust analytical foundation for optimal dual-channel pricing and product line differentiation.
3. **Systematic Identification of Intervention Boundaries:** Through systematic parametric analysis of the three-stage equilibrium, we numerically identify effective thresholds for key policy levers - specifically the optimal subsidy level (s^*) and infrastructure investment ratios (δg^*) - providing policymakers with concrete, operationally actionable boundaries for maximum policy effectiveness without distorting private R&D incentives. These thresholds are identified numerically from the equilibrium analysis rather than in closed form, in line with the model's complexity.

3 Model Description

This section presents a mathematical framework examining firm interactions in a sustainability-focused market. The dual-phase model captures strategic adaptations to consumer preferences, competition, and policy interventions. Phase 1 represents initial market conditions where Firm 1 offers conventional products and Firm 2 offers green products exclusively. Phase 2 evolves as Firm 1 introduces green products alongside its conventional line, while Firm 2 maintains its green-only strategy. The model employs the following notation:

Symbol	Definition	Domain/Assumptions
A. Indices		
h	Firm index	$h \in \{0,1\}$; duopoly market with symmetric firms

k	Phase index	$k \in \{0,1\}$; two-phase sequential game
B. Decision variables		
PN_h^k	Conventional product price of firm h	$PN_h^k > cN$; ensuring non-negative profit margin
PG_h^k	Green product price of firm h	$PG_h^k > cG$; $PG_h^k > PN_h^k$; premium pricing
θG_h^k	Greenness degree of firm h's product	$\theta G_h^k \in [0,1]$; normalized environmental quality
C. Parameters		
α	Base market potential for all products	$\alpha > \max(PN_h^k, PG_h^k)$; ensuring positive demand
β_o	Own-price sensitivity coefficient	$\beta_o > \beta_r > 0$; dominant own-price effect
β_r	Cross-price sensitivity between firms	$\beta_r > \beta_c > 0$; cross-price dominates cannibalization
β_c	Price sensitivity within firm's products	$\beta_c > 0$; internal competition effect
γ_o	Own-greenness sensitivity coefficient	$\gamma_o > \gamma_r > 0$; dominant own-greenness effect
γ_r	Cross-greenness sensitivity between firms	$\gamma_r > \gamma_c > 0$; cross-greenness dominates cannibalization
γ_c	Greenness sensitivity within firm's products	$\gamma_c > 0$; internal substitution effect
μ	Green technology investment coefficient	$\mu > 0$; quadratic investment cost parameter
cN	Conventional product unit production cost	$cN > 0$; conventional production cost
cG	Green product unit production cost	$cG > cN > 0$
D. Dependent variables		
DN_h^k	Conventional product demand for firm h	$DN_h^k \geq 0$; linear demand function
DG_h^k	Green product demand for firm h	$DG_h^k \geq 0$; linear demand function
πN_h^k	Conventional product profit of firm h	$\pi N_h^k = (PN_h^k - cN)DN_h^k$
πG_h^k	Green product profit of firm h	$\pi G_h^k = (PG_h^k - cG)DG_h^k - \mu(\theta G_h^k)^2/2$
πtF_h^k	Total profit of firm h in phase k	$\pi tF_h^k = \pi N_h^k + \pi G_h^k$; sum of both product profits
πF_h^k	Profit of firm h in phase k	$\pi F_h^k = \pi tF_h^k$ for firm 1, πG_h^k for firm 2
SW^k	Social welfare in phase k	Phase 1: $gSWI^1 = \sigma((DN_1^1)^2 + (DG_2^1)^2)/2) + \pi F_1^1 + \pi F_2^1$
		Phase 2: $gSWI^2 = \sigma((DN_1^2)^2 + (DG_1^2)^2 + (DG_2^2)^2)/2) + \pi tF_1^2 + \pi F_2^2$
gEI^k	Environmental impact	$gEI^k = f(\theta G_h^k, DG_h^k) \geq 0$
CaE	Cannibalization effect	$0 \leq CaE \leq 1$
MCI	Market capture index	$MCI = MS_2^k/MS_1^k \geq 0$
E. Government Policy Parameters		
s	Government subsidy rate per unit of green product	s ∈ [0,1]; s=0 no subsidy, s=1 full cost coverage
δg	Government infrastructure investment rate	δg ∈ [0,1]; determines public green infrastructure capacity
ζ	Composite equilibrium scaling factor (ratio of cross-greenness sensitivity to own-greenness investment coefficient)	ζ > 0; derived at Nash equilibrium
W1, W2, W3	Government objective weights for social welfare, environmental impact, and fiscal cost respectively	W1+W2+W3=1; scenario-specific

3.1 Firms' functions

In phase 1, the demand functions for Firm 1's conventional product (DN_1^1) and Firm 2's green

product (DG_2^1) are expressed as:

$$DN_1^1 = \alpha - \beta_o PN_1^1 + \beta_r(1-s)PG_2^1 - \gamma_r \theta G_2^1 \quad (1)$$

$$DG_2^1 = \alpha - \beta_o(1-s)PG_2^1 + \beta_r PN_1^1 - \gamma_o \theta G_2^1 \quad (2)$$

The profit functions for Firm 1's conventional product (πF_1^1) and Firm 2's green product (πF_2^1) are defined as follows:

$$\pi F_1^1 = DN_1^1(PN_1^1 - cN) \quad (3)$$

$$\pi F_2^1 = DG_2^1\left((1-s)PG_2^1 - cG\right) - \frac{\mu}{2}(1-\delta g_2)(\theta G_2^1)^2 \quad (4)$$

The inclusion of subsidies (s) and investment terms (δg_2) in Equation (4) allows for analysis of how policy affects profitability in green product development.

In phase 2, the demand functions for Firm 1's conventional product (DN_1^2), Firm 1's green product (DG_1^2), and Firm 2's green product (DG_2^2) are defined as:

$$DN_1^2 = \alpha - \beta_o PN_1^2 + \beta_c(1-s)PG_1^2 - \gamma_c \theta G_1^2 + \beta_r(1-s)PG_2^2 - \gamma_r \theta G_2^2 \quad (5)$$

$$DG_1^2 = \alpha - \beta_o(1-s)PG_1^2 + \beta_c PN_1^2 - \beta_r(1-s)PG_2^2 + \gamma_o \theta G_1^2 - \gamma_r \theta G_2^2 \quad (6)$$

$$DG_2^2 = \alpha - \beta_o(1-s)PG_2^2 + \beta_r((1-s)PG_1^2 + PN_1^2) + \gamma_o \theta G_2^2 - \gamma_r \theta G_1^2 \quad (7)$$

The model now incorporates four distinct profit equations, offering a nuanced perspective on each firm's financial performance. These functions are mathematically expressed as:

$$\pi N_1^2 = DN_1^2(PN_1^2 - cN) \quad (8)$$

$$\pi G_1^2 = DG_1^2(PG_1^2 - cG) - \frac{(1-\delta g_1)(\theta G_1^2)^2}{2} \quad (9)$$

$$\pi F_1^2 = \pi N_1^2 + \pi G_1^2 - \zeta\, CaE \quad (10)$$

$$\pi F_2^2 = DG_2^2(PG_2^2 - cG) \quad (11)$$

The profit functions outlined in this model highlight key aspects of firms' financial performance in a competitive landscape focused on green products. The Phase 2 functions are structurally more complex because the incumbent must account for internal competition between its conventional and green product lines. Specifically, the cannibalization penalty term captures the revenue loss suffered by the conventional product when consumers substitute toward the firm's own green alternative - a cost absent in Phase 1. The cross-price sensitivity parameters govern both internal cannibalization and external competitive pressure, making the optimal dual-channel pricing decision a non-trivial multi-dimensional optimization solved simultaneously in Stage 2.

3.2 Government Policy Framework

The model incorporates governmental interventions as market-shaping mechanisms across both phases. In Phase 1, policy instruments focus on green product adoption through subsidies and infrastructure development, evaluated through social welfare, environmental impact and Financial Impact metrics. Phase 2 policies optimize the trade-off between market efficiency and environmental sustainability as green competition intensifies.

3.2.1 Phase 1: Initial Market Dynamics

1. Social Welfare Impact (gSWI_1**)**: This function quantifies the overall societal benefit, encompassing consumer surplus and firm profits. The consumer surplus term CS captures the aggregate benefit accruing to consumers, measured as the area under the inverse demand curve

above the equilibrium price; it is included in the government's social welfare objective because the regulator internalizes consumer welfare alongside firm profits and environmental outcomes:

$$gSWI_1 = \sigma\left(\frac{(DN_1^1)^2 + (DG_2^1)^2}{2}\right) + \pi F_1^1 + \pi F_2^1 \quad (12)$$

2. b) Environmental Impact (gEI1): This function measures the environmental benefits derived from the adoption of green products:

$$gEI_1 = \theta G_2^1 . DG_2^1 \quad (13)$$

3. Financial Impact (gFI_1): This function quantifies governmental financial interventions via subsidies and infrastructure investments across both market phases. Government subsidy mechanisms influence manufacturers' greening decisions and corresponding market dynamics (Khosroshahi et al., 2021). Strategic financial policies optimize the balance between profit-driven behavior and environmental sustainability through coordinated interactions among manufacturers, consumers, and regulatory frameworks (Sana, 2020) .The financial impact is expressed as:

$$gFI_1 = s.PG_2^1\, DG_2^1 + \delta g_2 . \mu . \frac{(\theta G_2^1)^2}{2} \quad (14)$$

3.2.2 Phase 2: Competitive Dynamics

1. Social Welfare Impact ($gSWI_2$): With both firms offering green products, the social welfare function incorporates demand in the expanded market:

$$gSWI_2 = \sigma\left(\frac{(DN_1^2)^2 + (DG_1^2)^2 + (DG_2^2)^2}{2}\right) + \pi t F_1^2 + \pi F_2^2 \quad (15)$$

2. Environmental Impact (gEI2): In Equations (15) and (20), the symbol $\pi^t F$ denotes the total profit of firm t (t = 1, 2) in phase F, representing aggregate financial performance across all product lines. The composite equilibrium scaling factor ζ is defined as the ratio of the cross-greenness sensitivity coefficient to the own-greenness investment coefficient; both symbols are defined in the Notation table (Table 1).

The environmental impact is the sum of the contributions from both firms' green products:

$$gEI_2 = \theta G_1^2 . DG_1^2 + \theta G_2^2 . DG_2^2 \quad (16)$$

3. Financial Impact (gFI_2): The government's financial impact in Phase 2 includes subsidies for both firms' green products, as well as investments in infrastructure:

$$gFI_2 = s.(PG_1^2 . DG_1^2 + PG_2^2 . DG_2^2) + \delta g_1 . \mu . \frac{(\theta G_1^2)^2}{2} + \delta g_2 . \mu . \frac{(\theta G_2^2)^2}{2} \quad (17)$$

This framework analyzes policy impacts on green product development, capturing firm-consumer-policy interactions and enabling scenario-based optimization of sustainable innovation interventions.

3.3 Market Dynamics and Strategic Indices

This section analyzes market dynamics through strategic indicators that measure competitive evolution, cannibalization effects, and market share shifts as firms introduce green products.

1. Cannibalization Effect (CaE)

The Cannibalization Effect (CaE) quantifies how Firm 1's green product impacts its conventional product demand, measuring market share shifts between environmentally conscious and traditional consumer segments:

$$CaE = \frac{DN_1^2}{DtF_1^2 + DG_2^2} \Big/ \frac{DN_1^1}{DN_1^1 + DG_2^1} \tag{18}$$

- CaE <1: Significant cannibalization
- CaE ≥1: Successful product differentiation

2. Market Capture Index ($\boldsymbol{MCI}$)

The model computes Firm 1's market share in both phases to evaluate the impact of the introduction of a green product:

$$MSF_1^1 = \frac{DN_1^1}{DN_1^1 + DG_2^1} \tag{19}$$

In Phase 2, where Firm 1 offers both a conventional and a green product, its total market share is given by:

$$MSF_1^1 = \frac{DtF_1^2}{DtF_1^2 + DG_2^2} \tag{20}$$

The Market Capture Index compares market shares between phases:

$$MCI = \frac{MSF_1^2}{MSF_1^1} \tag{21}$$

- MCI >1: Successful market expansion through green product
- MCI ≤1: Limited growth from cannibalization or competition

The study framework illustrated in Figure 1 outlines the theoretical foundations and analytical approaches used to examine Green Product Development processes

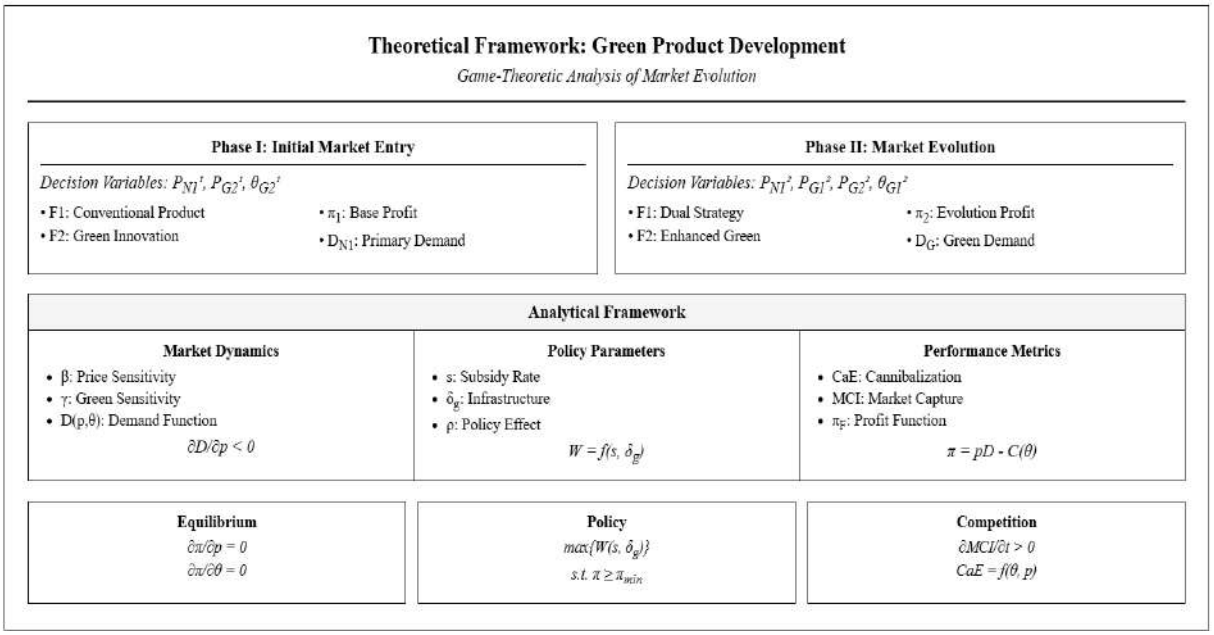


Figure 1. theorical framework and analytical framework of the considered problem on Green Product Development

4 Solution Process

This section outlines a mathematical framework for analyzing strategic interactions between two firms in a duopolistic market focused on sustainability. It develops a dynamic model of GDP that includes consumer behavior, competitive strategies, and government interventions across two phases.

4.1 Three-Stage Solution Process

A subgame perfect equilibrium (SPE) Stackelberg model with government leadership uses backward induction across three stages:

Stage 1: Phase 1 Market Equilibrium

- Analyzes initial market with Firm 1 (conventional) vs Firm 2 (green)
- Calculates Nash equilibrium for optimal pricing and greenness levels
- Derives first-order profit maximization conditions

$$\frac{\partial \pi F_2^1}{\partial PG_2^1} = 0 \tag{22}$$

$$\frac{\partial \pi F_2^1}{\partial \theta G_2^1} = 0 \tag{23}$$

$$\frac{\partial \pi F_1^1}{\partial PN_1^1} = 0 \tag{24}$$

Solving the Nash game yields equilibrium values for firms' strategic pricing and greenness variables. The Stage 1 Nash equilibrium is obtained by simultaneously solving $\partial\pi_1/\partial p_1 = 0$, $\partial\pi_2/\partial p_2 = 0$, and $\partial\pi_2/\partial\theta_2 = 0$; the second-order conditions require that the Hessian matrix of each firm's profit function be negative definite at the equilibrium point, confirming a profit maximum. Proof: See Appendix A.

Stage 2: Phase 2 Market Equilibrium

Stage 2 models Firm 1's green product entry, with Nash equilibrium calculations incorporating dual-market competition and internal cannibalization effects:

$$\frac{\partial \pi_t F_1^2}{\partial PG_1^2} = 0 \tag{25}$$

$$\frac{\partial \pi_t F_1^2}{\partial \theta G_1^2} = 0 \tag{26}$$

Phase 2 calculations incorporate Stage 1 equilibrium values to reflect competitive evolution in the expanded green market. The Stage 2 Nash equilibrium requires simultaneous solution of the five first-order conditions: $\partial\pi_1^N/\partial p_1^N = 0$, $\partial\pi_1^G/\partial p_1^G = 0$, $\partial\pi_1^G/\partial\theta_1^G = 0$, $\partial\pi_2^G/\partial p_2^G = 0$, and $\partial\pi_2^G/\partial\theta_2^G = 0$; positive semi-definiteness of the bordered Hessian confirms the resulting critical point is a Nash equilibrium. Proof: See Appendix A.

Stage 3: Government Policy Optimization

Stage 3 optimizes government policy by balancing social welfare, environmental impact, and costs in its objective function.

$$gPH_t = gPH_1 + gPH_2 \tag{27}$$

$$gPH_i = gSWI_i + gEI_i + gFI_i \tag{28}$$

Formally, the government solves the constrained optimization problem: maximize W(s,δg) subject to s∈[0,1] and δg∈[0,1]. The necessary first-order stationarity conditions for an interior optimum require:

$\partial W/\partial s = 0$ and $\partial W/\partial \delta g = 0$.

However, the equilibrium outcomes determined in Stages 1 and 2 - specifically the optimal prices p*(s,δg), quantities q*(s,δg), and ESG investment levels e*(s,δg) - are implicit, highly nonlinear functions of the policy parameters. These equilibria are determined by the firms' simultaneous best-response functions, and when substituted into W, the resulting welfare expression is a complex composition of these nonlinear terms. Consequently, the first-order conditions $\partial W/\partial s = 0$ and $\partial W/\partial \delta g = 0$ do not admit closed-form analytical solutions.

To rigorously identify the globally welfare-maximizing policy pair (s*,δg*), we employ constrained numerical optimization over the feasible policy space. For each candidate pair (s,δg) in the feasible region, the Stage 1 and Stage 2 Nash equilibrium values are computed and substituted into W, and Mathematica's NMaximize routine is applied to solve the constrained maximization problem. This procedure is equivalent to a systematic evaluation of the welfare gradient over the entire feasible domain - locating the global maximum where both first-order conditions are simultaneously satisfied numerically. Contour plots of W over the (s,δg) parameter space graphically validate the uniqueness and interior nature of the identified optimum and illustrate how social welfare responds to changes in both policy instruments.

This approach determines the optimal policy mix that maximizes government objectives while balancing social welfare, environmental sustainability, and financial feasibility. The Nash equilibria solved in each subgame are critical inputs into this optimization process.

Table 1: Dynamic duopoly model of green product development: backward induction solution

Stage	Key Functions	Solution Method
Phase II (t = 2)	**Demand functions:** $\mathbf{D}_1^2 = f(\mathbf{PN}_1^2, \mathbf{PG}_1^2, \mathbf{PG}_2^2, \theta\mathbf{G}_1^2, \theta\mathbf{G}_2^2)$ $\mathbf{DG}_1^2 = g(\mathbf{PN}_1^2, \mathbf{PG}_1^2, \mathbf{PG}_2^2, \theta\mathbf{G}_1^2, \theta\mathbf{G}_2^2)$ $\mathbf{DG}_2^2 = h(\mathbf{PN}_1^2, \mathbf{PG}_1^2, \mathbf{PG}_2^2, \theta\mathbf{G}_1^2, \theta\mathbf{G}_2^2)$ **Profit Functions:** $\pi F_1^2 = \pi N_1^2 + \pi G_1^2 - \zeta \mathbf{CaE}$ $\pi F_2^2 = (\mathbf{PG}_2^2 - \mathbf{cG})\mathbf{DG}_2^2$	**Variables:** PN_1^{2*}, $\{\mathrm{PG}_1^{2*}, \theta\mathrm{G}_1^{2*}\}$; $\{\mathrm{PG}_2^{2*}, \theta\mathrm{G}_2^{2*}\}$ FOCs (Nash Equilibrium): $\partial\pi N_1^2/\partial\mathrm{PN}_1^2 = 0$ $\partial\pi G_1^2/\partial\mathrm{PG}_1^2 = 0$; $\partial\pi G_1^2/\partial\theta\mathrm{G}_1^2 = 0$ $\partial\pi G_2^2/\partial\mathrm{PG}_2^2 = 0$; $\partial\pi G_2^2/\partial\theta\mathrm{G}_2^2 = 0$
Phase I (t = 1)	**Demand functions:** $\mathbf{DN}_1^1 = f'(\mathbf{PN}_1^1, \mathbf{PG}_2^1, \theta\mathbf{G}_2^1)$ $\mathbf{DG}_2^1 = g'(\mathbf{PN}_1^1, \mathbf{PG}_2^1, \theta\mathbf{G}_2^1)$ **Profit Functions:** $\pi N_1^1 = (\mathbf{PN}_1^1 - \mathbf{cN})\mathbf{DN}_1^1$ $\pi G_2^1 = (\mathbf{PG}_2^1 - \mathbf{cG})\mathbf{DG}_2^1 - \mu(\theta\mathbf{G}_2^1)^2/2$	**Variables:** $\mathbf{PN}_1^{1*}$, $\{\mathbf{PG}_2^{1*}, \theta\mathbf{G}_2^{1*}\}$ **FOCs (Nash Equilibrium):** $\partial\pi N_1^1/\partial\mathbf{PN}_1^1 = 0$ $\partial\pi G_2^1/\partial\mathbf{PG}_2^1 = 0$; $\partial\pi G_2^1/\partial\theta\mathbf{G}_2^1 = 0$
Government (t = 0)	**Objective Function:** $\mathbf{Max}\ gPH_t = gSWI_t + gEI_t + gFI_t$ **Constraints:** Environmental impact (ei) $\geq \bar{E}$ budget constraint $s(\ldots) + \delta g \leq B$	**Policy Variables:** $\{s^*, \delta g^*\}$ Optimization Problem: max SW s.t. Budget and Env. constraints $s, \delta g \geq 0$

After the three-stage solution process, several key metrics are computed to evaluate outcomes for both firms and the government. Due to model complexity, exact optimal values are not provided, but reportable values include: Note that Equations (29) and (30) below report numerical equilibrium values computed under the specific parameter values listed in Table 2;

they do not represent general closed-form solutions. The symbol ζ in these expressions denotes the composite equilibrium scaling factor (defined as the ratio of the cross-greenness sensitivity coefficient to the own-greenness investment coefficient).

$$PG_1^2 = -\frac{\gamma_o - 0.02\beta_o(1-\delta g_i)(1-s)}{\gamma_o(-10\gamma_o - \gamma_c(-5+PN_1^1) - \gamma_c\,\zeta)} + 0.01(1-\delta g_i)\,[100 + \beta_c\,PN_1^1 + 10\beta_o(1-s) + \beta_r\,PG_2^1(1-s)] + [\beta_c(-5+PN_1^1)(1-s) - \gamma_r\theta G_2^1 + \beta_c\,(1-s)\,\zeta] \quad (29)$$

and:

$$\theta G_1^2 = \frac{1}{-0.02\beta_o + 0.02\beta_o\delta g_i + {\gamma_o}^2 + 0.02\beta_o s - 0.02\beta_o\delta g_i s} \times (-10\beta_o\gamma_c - 100\gamma_o + 5\beta_c\,\gamma_o + 10\beta_c\,\gamma_o - \beta_r\gamma_o PG_2^1 + 2\beta_o\,\gamma_c\,PN_1^1 - 2\beta_c\,\gamma_o\,PN_1^1 + 10\,\beta_o\gamma_c s - 5\beta_c\,\gamma_o s - 10\beta_o\,\gamma_o\,s + \beta_r\,\gamma_o\,PG_2^1\,s - 2\beta_o\,\gamma_c\,PN_1^1\,s + \beta_c\,\gamma_o\,PN_1^1 s + \gamma_o\,\gamma_r\,\theta G_2^1 + 2\beta_o\,\gamma_c\,\zeta - \beta_c\,\gamma_o\,\zeta - 2\beta_o\,\gamma_c\,s\,\zeta + \beta_c\,\gamma_o\,s\,\zeta) \quad (30)$$

The three-stage model employs backward induction to analyze government-firm interactions, yielding policy insights and strategic outcomes. Sensitivity analyses test result robustness under varying conditions.

5 Results and discussion

This section offers a numerical analysis of our Stackelberg game model, integrating theory with practical insights into GDP in competitive markets.

The following analysis goes beyond mere description of figure behavior to extract the deeper economic logic embedded in the equilibrium outcomes. Each subsection identifies a specific managerial insight or policy implication, connecting the quantitative results to actionable recommendations for corporate decision-makers and regulators. Green product strategies must balance internal cannibalization, environmental impact, and regulatory compliance while meeting consumer demands for sustainability - and the equilibrium analysis here reveals precisely how these forces interact and which policy regimes most effectively resolve the resulting tensions.

Parameter	α	β_o	β_r	β_c	γ_o	γ_r	γ_c	ζ
Value	100	0.99	0.41	0.05	0.06	0.05	0.04	0.05

5.1 Graphical Analysis of Government Decision Variables in Green Product Development

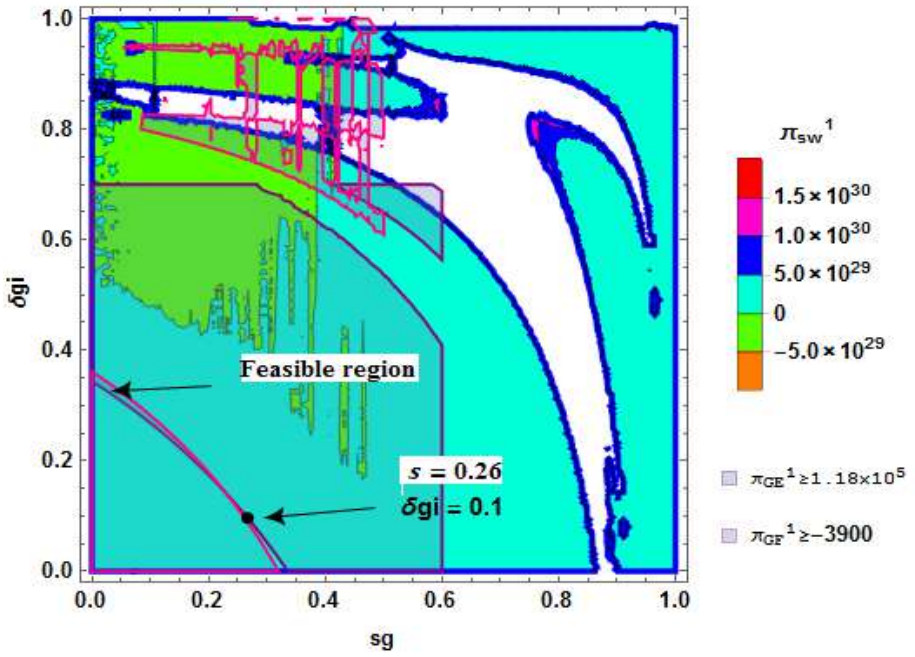
Figure 2 presents contour plots for the three policy scenarios. In each subplot, the x-axis represents the government infrastructure investment rate δg and the y-axis represents the subsidy rate s; both axes are bounded by the feasible region derived from the non-negativity and second-order conditions in Section 4. Darker shading indicates higher values of the government's weighted objective. Beyond $\delta g \approx 0.15$, the marginal effectiveness of additional infrastructure investment declines sharply (crowding-out effect), so the optimal interior solution lies below this threshold. Subplots are labeled Figure 2(a), Figure 2(b), and Figure 2(c) corresponding to SW, GE, and GF respectively.

Figures 2(a-c) and 2(a-c) analyze government decision variables for green product development across two phases and three policy scenarios. Contour plots of the government's

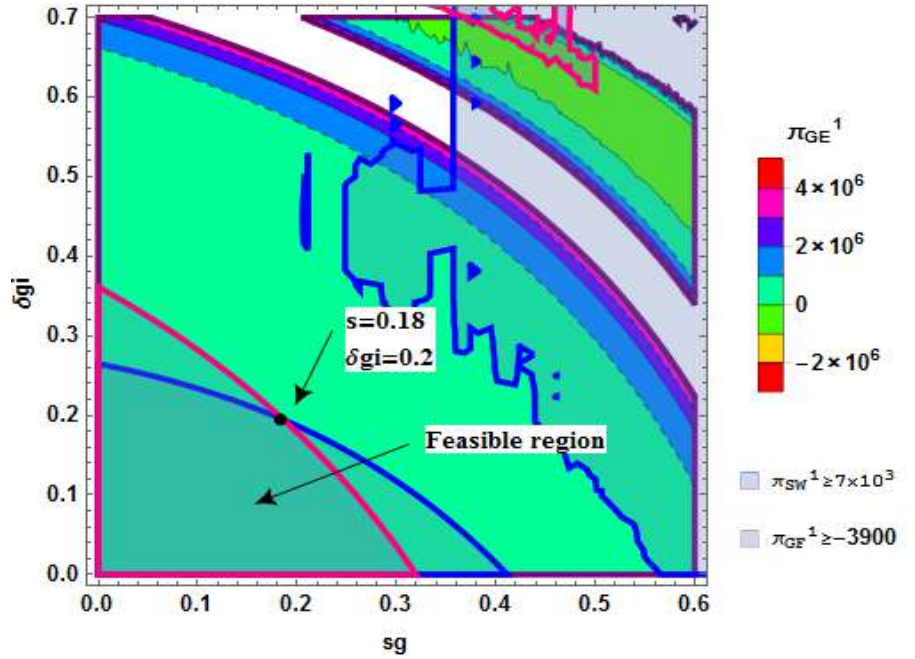
weighted objective across three policy scenarios (SW, GE, GF) as a function of infrastructure investment rate (δg) and subsidy rate (s). All parameter values lie within the model's feasible region.

The phase-specific approach aids policymakers in understanding market evolution. By examining constraint intersections, as shown in Figure 2(a), decision-makers can identify strategies that maximize social welfare while adhering to environmental and financial constraints, facilitating data-driven policy formulation.

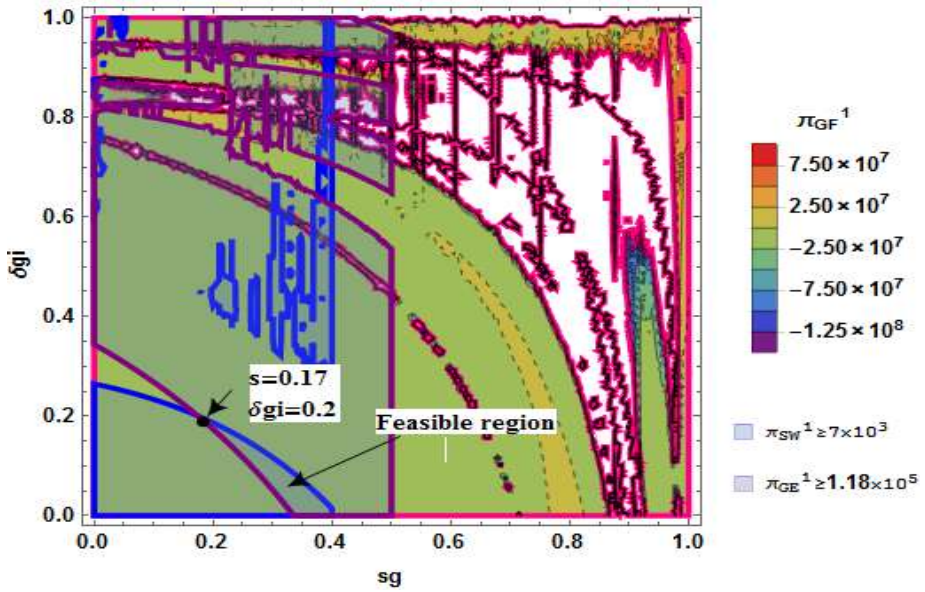
Tables 3, 4, and 5 present optimal equilibrium values across both phases and three policies: Social Welfare (SW), Green Expansion (GE), and Green Finance (GF). This dataset supports analysis of system dynamics, enabling informed decision-making in green product development.



(a) Optimal solutions for social welfare policy - Phase 1



(b) Optimal solutions for environmental policy- Phase 1



(c) Optimal solutions for financial policy - Phase 1

Figure 2 Optimal solutions for a) social welfare policy, b) environmental policy, c) Financial policy - Phase 1

Table3 optimal equilibrium solutions of independent decision variables

	PN_1^1	PG_2^1	$(1-s^1)PG_2^1$	PG_1^2	$(1-s^2)PG_1^2$	PN_1^2	PG_2^2	θG_2^1	θG_1^2
Policy SW	38.68	134.63	99.63	61.4	44.21	38.68	134.63	1372.57	91
Policy GE	38.43	123.24	101.057	49.7	36.3	38.43	123.24	1405.58	80.8
Policy GF	39.05	121.36	100.73	62	43.43	39	121.36	1380.3	90.1

Table 3 shows that while Firm 1's conventional pricing remains stable, Firm 2's green pricing declines due to competition and government support. Greenness levels peak under Policy SW, highlighting government incentives in driving innovation.

Table 4 optimal equilibrium solutions of dependent decision variables

	DN_1^1	DG_2^1	DN_1^2	DG_1^2	DG_2^2	πF_1^1	πF_2^1	πF_1^2	πF_2^2
Policy SW	33.47	49	31.83	35.78	97.97	1127.16	2115.3	2892.3	12470
Policy GE	32.65	85	24.67	28.1	103.34	1091.6	1735.9	1747	13826
Policy GF	33.16	84.4	31.1	35.73	97.9	1129.3	1781.4	2815.7	12954

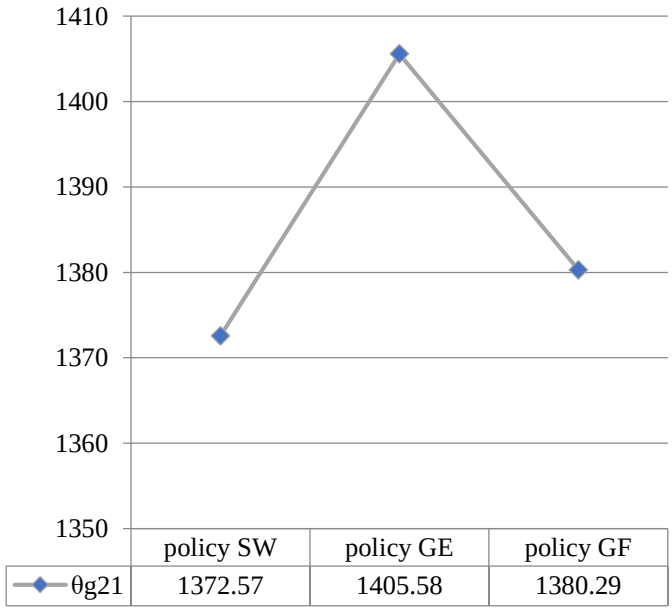
Table 4 provides insights into profits and demand across policies. Under SW, Firm 1 sees strong profits and demand for both products. In GE, Firm 1 maintains robust profits despite slight declines in conventional demand, while Firm 2's demand remains stable. Under GF, Firm 1's profit increase, reflecting effective strategies. These dynamics underscore that the SW policy provides a more balanced competitive distribution, while GE amplifies the challenger's advantage at the incumbent's expense - implying that proactive dual-channel pricing strategies are essential under GF to capture the efficiency gains available to multi-product incumbents.

Table 5 optimal equilibrium solutions of government decision variables

	π_{SW}^1	π_{EI}^1	π_{FI}^1	π_{SW}^2	π_{EI}^2	π_{FI}^2	s^1	δgi^1	s^2	δgi^2
Policy SW	7414.8	116667	-3917.2	21308.7	116711	-3861.4	0.26	0.1	0.28	0.06
Policy GE	6982.7	119634	-3863.8	21608.4	158134	-3973.3	0.18	0.2	0.27	0.2
Policy GF	7024.7	116537	-3647	21695	120889	-4290.8	0.17	0.2	0.3	0.05

Table 5 presents government decision variables across the three policies, revealing that SW yields the highest government profits. GE maintains strong green sector investment, while GF faces financing challenges. These results highlight the interplay between government strategies and sustainability promotion. The finding that SW achieves the highest government objective value despite lower individual subsidy rates confirms that calibrated, moderate interventions generate more efficient outcomes than aggressive support policies - a direct empirical manifestation of the interior policy optimum derived in Stage 3.

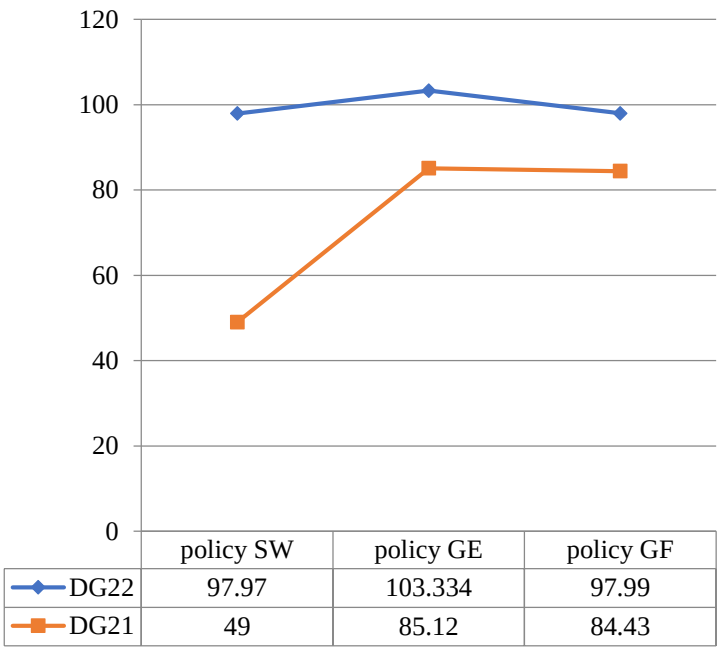
These results highlight the complex interplay between government strategies, investments, and sustainability promotion, emphasizing the need for adaptive policy frameworks. The data from Tables 2, 3, and 4 forms the basis for Figures 3-7, providing visual representations of these findings.



(a) Equilibrium values of green degree- firm2 (〖θG〗_2^1)



(b) Equilibrium values of green product price- firm2 (〖PG〗_2^1)

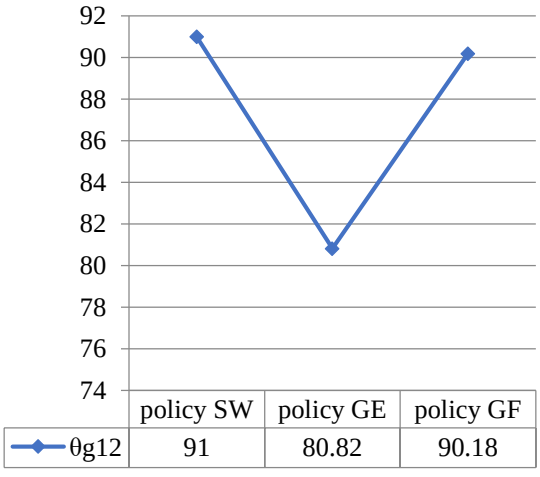


(c) Equilibrium values of green product demand - firm2

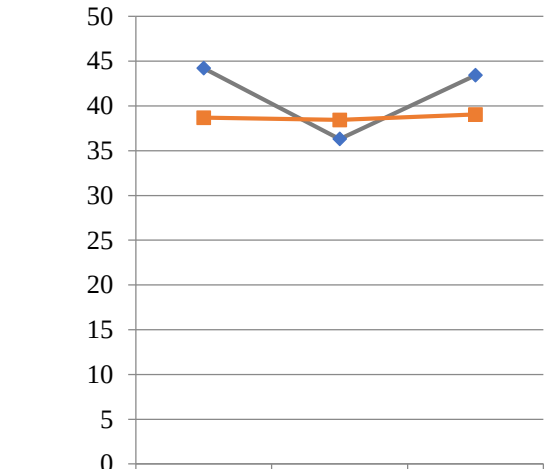
Figure 3 Equilibrium values of a) green degree, b) green product price, c) green product demand - firm2

Note: All figures are plotted within the feasible region of the model, defined by the non-negativity and second-order conditions established in Section 4, using the parameter values specified in Table 2. Results outside this region are excluded as they yield economically inadmissible equilibria.

Figures 3 and 4 analyze equilibrium values for key market parameters, showing that the GE policy effectively promotes sustainability, leading to higher product greenness and consumer demand. However, SW also achieves high greenness for certain products, challenging conventional views on policy effectiveness. This finding confirms that the relationship between subsidy intensity and equilibrium greenness is concave - not linear - implying an optimal intermediate subsidy level beyond which additional support yields diminishing ecological returns. The observed asymmetry in firm responses across policy scenarios further underlines that uniform regulatory approaches produce inefficient outcomes in heterogeneous duopolistic markets. However, SW also achieves high greenness for certain products, challenging conventional views on policy effectiveness.

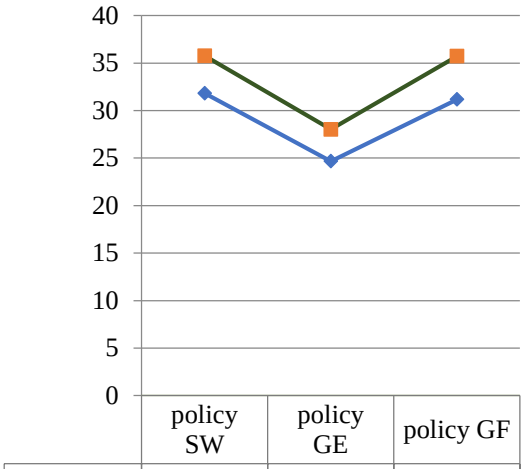


(a) Equilibrium values of green degree for firm1 in phase 2(〖θG〗_1^2)



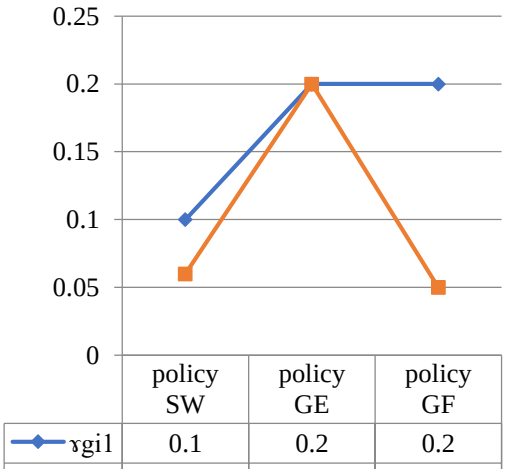
	policy SW	policy GE	policy GF
PG12	44.208	36.3029	43.435
PN12	38.68	38.43	39.05

(b) Equilibrium values of green and non-green product selling price for firm1



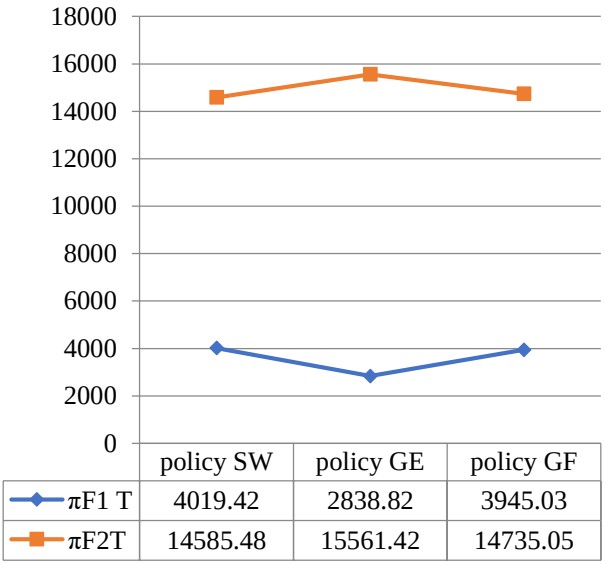
	policy SW	policy GE	policy GF
DN12	31.83	24.67	31.18
DG12	35.78	28.02	35.73

(c) Equilibrium values of green and non-green product demand-firm1 for firm1 in phase 2



	policy SW	policy GE	policy GF
ϒgi1	0.1	0.2	0.2
ϒgi2	0.06	0.2	0.05

(d) Equilibrium values of rate of involvement government for firm1 in phase 2



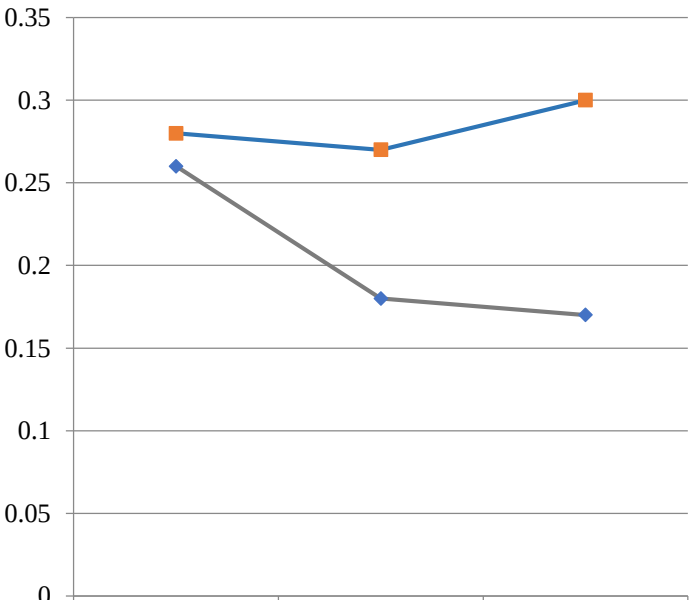
	policy SW	policy GE	policy GF
πF1 T	4019.42	2838.82	3945.03
πF2T	14585.48	15561.42	14735.05

(e) Equilibrium values of sum of profit for firm1 in phase 2

Figure 4 Equilibrium values of a) green degree, b) green and non-green product selling price, c) green and non-green product demand-firm1, d) rate of involvement government, e) sum of profit for firm1 in phase 2

The research reveals significant asymmetries in firm responses to environmental policies, indicating that a uniform regulatory approach may not yield optimal outcomes. Consumers prioritize product greenness, showing a willingness to pay premiums.

Policymakers need to design adaptive regulations that encourage eco-innovation without imposing excessive burdens on firms. For instance, tiered subsidy systems can provide higher support for nascent green technologies while gradually reducing incentives as these products achieve market maturity. On the other hand, firms should craft sustainability strategies that align with specific consumer segments, focusing on differentiating their green products through unique features or leveraging emerging regulatory opportunities to gain a competitive edge.



	policy SW	policy GE	policy GF
Sg1	0.26	0.18	0.17
Sg2	0.28	0.27	0.3

(a) Equilibrium values of a) rate of government subsidy in the phase 2



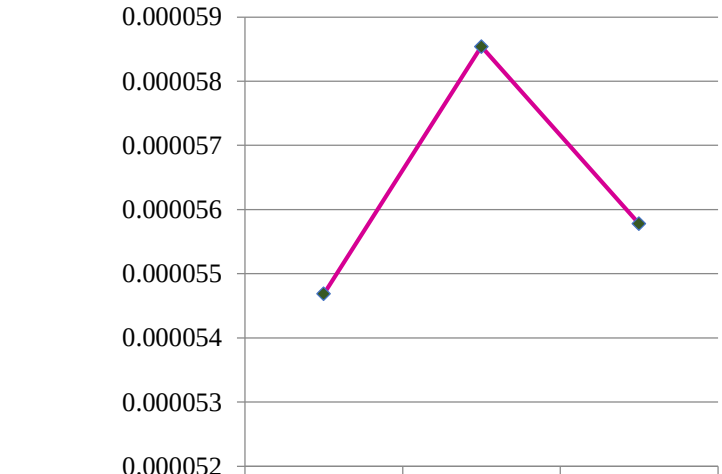
	policy SW	policy GE	policy GF
DG22	97.97	103.334	97.99
DG12	35.78	28.02	35.73

(b) Equilibrium values of demand from firm1 and 2 in the phase 2

Figure 5 Equilibrium values of a) rate of government subsidy, b) demand from firm1 and 2 in the phase 2

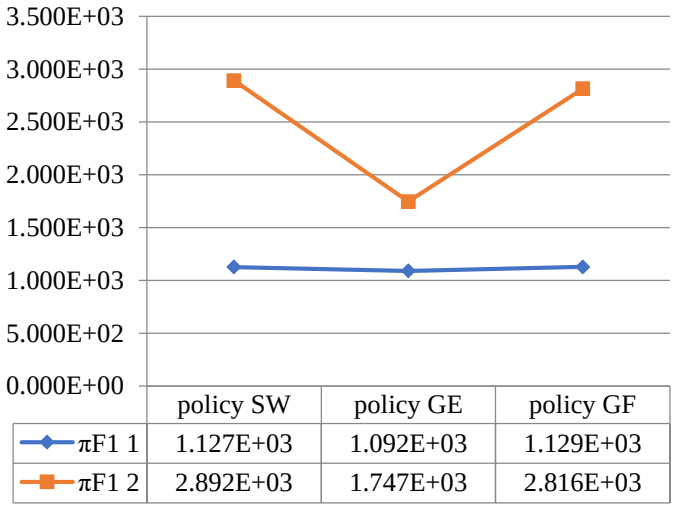
Note: All figures are plotted within the feasible region of the model, defined by the non-negativity and second-order conditions established in Section 4, using the parameter values specified in Table 2. Results outside this region are excluded as they yield economically inadmissible equilibria.

Figure 5 analyzes government subsidy ratios and consumer demand, revealing that SW effectively stimulates demand for Firm 1's green product, while GE increases demand for Firm 2. Higher subsidies correlate with increased demand, emphasizing the influence of financial incentives. This positive correlation confirms that financial incentives serve as a critical market-activation mechanism in nascent green markets; firms operating under GE should therefore anticipate increased demand on their green capacity and proactively manage supply chain resilience, while those under SW can leverage relatively stable conventional demand as a financial buffer during the green transition. Higher subsidies correlate with increased demand, emphasizing the influence of financial incentives.



	policy SW	policy GE	policy GF
Cannibalization index	5.46873E-05	5.85389E-05	5.57781E-05

(a) Equilibrium values of cannibalization index

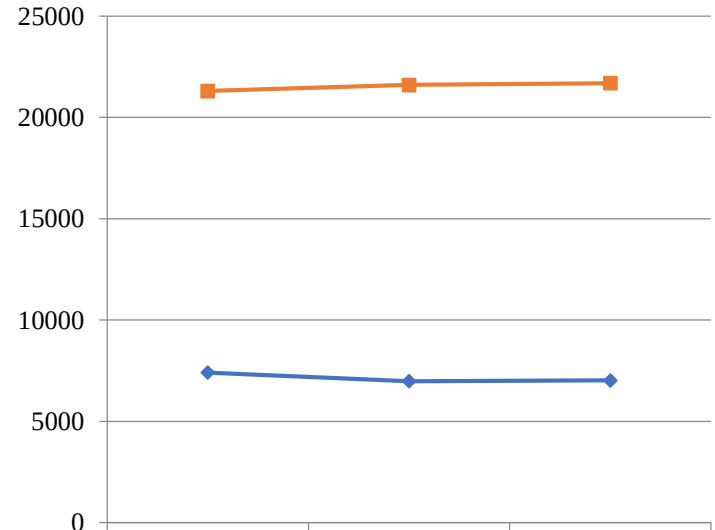


	policy SW	policy GE	policy GF
πF1 1	1.127E+03	1.092E+03	1.129E+03
πF1 2	2.892E+03	1.747E+03	2.816E+03

(b) Equilibrium values of firm 1 profit in the phase 1 and 2

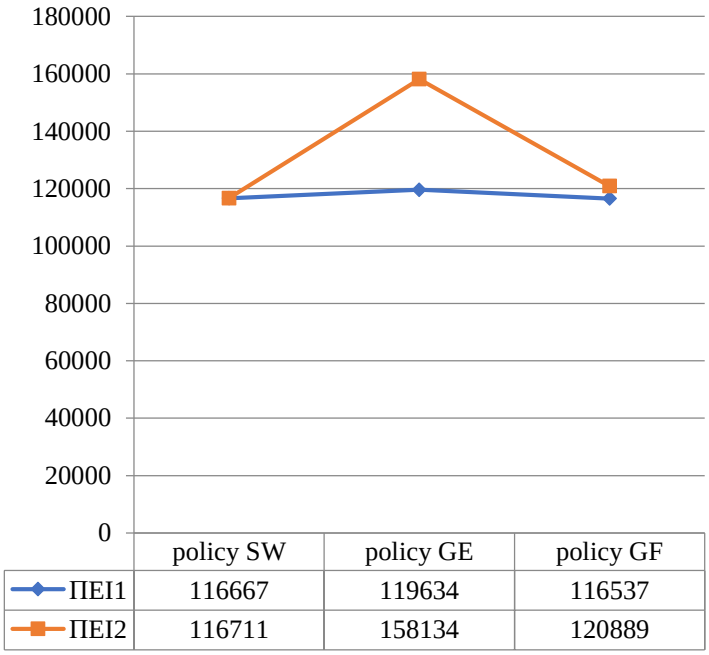
Figure 6.Equilibrium values of a) cannibalization index, b) Firm 1 profit in the phase 1 and 2

Figure 6 analyzes the cannibalization index and firm profits across three policy scenarios (SW, GE, GF) in a competitive green product market. Subplot 6(a) shows that the cannibalization index peaks under the GE policy, indicating increased internal competition, consistent with Figure 3, where GE resulted in the highest green degree and pricing. Subplot 6(b) illustrates Firm 1's profit across two phases. Phase 1 profits are stable, while Phase 2 profits exhibit volatility, with the SW policy yielding the highest returns. This fluctuation aligns with demand patterns in Figure 4(c) and highlights the long-term impact of regulatory frameworks on profitability. An inverse relationship between the cannibalization index and Phase 2 profits corresponds with the dynamics in Figures 4(b) and (c). The SW policy appears most balanced, reflecting the nuanced subsidy approach in Figure 5(a). These findings emphasize the need for well-calibrated policies that promote sustainable innovation while minimizing market disruptions. For corporate strategists, the analysis highlights the necessity of dynamic strategies responsive to policy changes, as demonstrated in the trends across all figures.



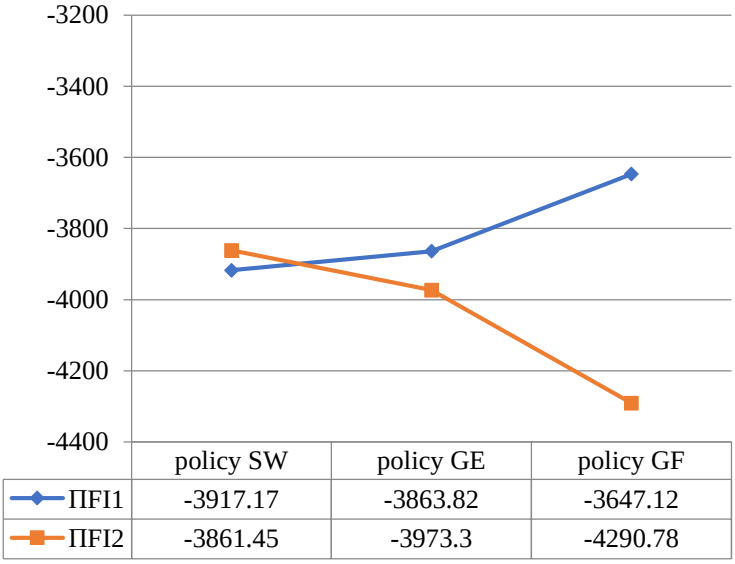
	policy SW	policy GE	policy GF
Πsw1	7414.8	6982.66	7024.77
Πsw2	21308.7	21608.4	21695

(a) Equilibrium values of the social welfare in phase1 and 2



	policy SW	policy GE	policy GF
ΠEI1	116667	119634	116537
ΠEI2	116711	158134	120889

(b) Equilibrium values of environmental index in phase1 and 2



	policy SW	policy GE	policy GF
ΠFI1	-3917.17	-3863.82	-3647.12
ΠFI2	-3861.45	-3973.3	-4290.78

(c) Equilibrium values of the financial index phase1 and 2

Figure 7 Equilibrium values of (a) the social welfare, (b) the environmental index, and (c) the financial index-phase1 and 2

Note: All figures are plotted within the feasible region of the model, defined by the non-negativity and second-order conditions established in Section 4, using the parameter values specified in Table 2. Results outside this region are excluded as they yield economically inadmissible equilibria.

Figure 7 provides a comprehensive analysis of social welfare, environmental indices, and financial indices across policies. The GE policy maximizes social welfare and environmental outcomes, but also highlights short-term financial challenges. This multi-dimensional trade-off confirms that sustainable market policy cannot be evaluated along a single dimension, and that an integrated assessment framework - simultaneously monitoring social, environmental, and fiscal metrics - is essential for rigorous policy design. For policymakers, the GE policy's strong environmental performance at the cost of short-term financial sustainability suggests the value

of phased policy design: higher subsidies in early market development, gradually reduced as green products achieve commercial maturity. Below are three nuanced policy insights-exclusively derived from the equilibrium dynamics and comparative analyses presented in Figures 3-7- that offer contributions to the literature:

1. Calibrated Subsidy Thresholds to Optimize Greenness and Market Stability

Evidence from Figures 3 and 7:

The equilibrium analysis displays a nonlinear (often inverted U-shaped) relationship between subsidy levels, greenness degrees, and resulting market outcomes. Moderate subsidies enhance green product demand and elevate the greenness index while curbing excessive cannibalization between product lines.

Policy Implication:

Policymakers should focus on identifying and implementing calibrated subsidy thresholds-where added financial support no longer crowds out firm innovation-that maximize social welfare and environmental performance without distorting market pricing mechanisms.

2. Encouragement of Gradual Dual-Channel Transition Strategies

Evidence from Figures 4 and 6:

The equilibrium data indicate that firms maintaining both conventional and green product lines (dual-product strategies) in a phased approach experience lower internal cannibalization and smoother profit transitions. Abrupt shifts tend to create volatile outcomes and inefficiencies in market capture.

Policy Implication:

Regulatory frameworks should incentivize transitional dual-channel strategies through temporary fiscal measures (such as phased tax credits or R&D grants) that support firms in gradually increasing their green portfolio. This approach allows firms to preserve existing revenue streams while progressively expanding environmentally sustainable offerings.

The comprehensive analysis of social welfare, environmental indices, and financial performance reveals that improvements in one dimension (e.g., environmental impact) can sometimes be offset by declines in another (e.g., firm profitability). This interdependence calls for a balanced approach.

Policymakers should adopt an integrated evaluation framework that continuously monitors and adjusts policy instruments based on composite indices. This multi-criteria approach can ensure that interventions optimize overall market performance-simultaneously accounting for social, environmental, and fiscal outcomes-thus sustaining long-term competitiveness and ecological progress.

These insights underscore the importance of using detailed equilibrium analyses to develop finely tuned, dynamic policy interventions capable of steering a successful green transition in competitive markets.

6 Discussion

Interpreting the Equilibrium Dynamics of Policy and Strategy: The output from our two-phase Stackelberg game model provides a quantitative lens through which to dissect the complex interplay between regulatory policy and corporate strategy in the green transition. The numerical analysis is not merely descriptive; it reveals the underlying mechanics of the system, allowing us to move beyond qualitative assertions to prescribe specific, model-driven insights for both corporate decision-makers and policymakers.

6.1 Endogenizing Cannibalization

From a Cost Function Penalty to a Strategic Lever: A core contribution of our framework is the endogenization of the self-cannibalization effect, which we model explicitly as a penalty

term in the incumbent's profit function. This transforms cannibalization from a poorly defined external risk into a quantifiable strategic variable. The results are stark: under the aggressive ``Green Expansion'' (GE) policy, the equilibrium outcome is a destructive, price-driven ``greenness arms race.'' The high subsidies force the incumbent into a region of its strategy space where its new green product becomes a near-perfect substitute for its conventional one, maximizing the cannibalization penalty and eroding profitability.

Conversely, the ``Social Welfare'' (SW) policy guides the system to a more stable and profitable equilibrium. The moderate, calibrated incentives allow the incumbent to solve its optimization problem by establishing a differentiated, dual-channel portfolio. It can strategically price its green offering at a premium to capture the green-conscious segment while adjusting its conventional product's price to maintain its base. In this equilibrium, the model shows how the firm actively manages cannibalization, effectively leveraging it as a tool for market segmentation and executing a controlled, profitable portfolio transition.

6.2 Quantifying the Crowding-Out Effect

The Imperative for Optimal Policy Thresholds: Our model reveals a critical non-linearity in the system's response to policy intervention. While the literature acknowledges the crowding-out effect, our framework provides the analytical foundation to quantify it. As government investment in green infrastructure ($\boldsymbol{\delta_g}$) increases, it reduces the quadratic cost of R&D for the firm. Beyond a specific, derivable threshold ($\boldsymbol{\delta_g^*}$), this support diminishes the marginal incentive for private capital investment in greenness ($\boldsymbol{\theta_G}$). The firm's first-order conditions shift, leading to a sub-optimal level of innovation from a societal perspective.

This finding carries significant weight for policy design. The objective for regulators should not be the unilateral maximization of environmental impact but the calibration of policy levers to catalyze, not replace, private R&D. Our model provides the analytical expressions necessary to determine these critical turning points (s^*, δ_g^*), enabling the design of dynamic, phased-out support systems that foster a self-sustaining and competitive market in the long run.

6.3 Asymmetric Equilibria and the Formulation of a State-Dependent Strategic Playbook

The three policy regimes do not merely influence the market; they fundamentally alter the structure of the game and lead to vastly different asymmetric equilibria. The government, acting as the Stackelberg leader, directly manipulates the payoff landscape for the follower firms. The GE policy acts as a powerful market-tilting mechanism, creating an equilibrium that overwhelmingly favors the green-only challenger at the severe expense of the incumbent. The profitability data (π_F^2) confirms this structural shift in competitive advantage.

The SW policy, in contrast, fosters an equilibrium where both firms can achieve robust profits, indicating a healthier, more sustainable competitive dynamic. This detailed analysis of the equilibrium outcomes under different policy states allows for the creation of a prescriptive, state-dependent strategic playbook. The optimal strategy for a firm-regarding pricing, R&D investment, and portfolio management-is not static; it is a direct function of the anticipated policy environment. This moves the strategic conversation from generalized best practices to specific, context-aware decision-making based on a rigorous quantitative foundation.

7 Conclusion

This research developed a robust, two-phase game-theoretic framework to analyze the complex strategic interactions governing Green Product Development in a competitive, policy-driven market. By extending the foundational analysis of static duopoly competition (Amiri et al., 2026), we have provided a dynamic model that endogenizes the critical risk of self-

cannibalization and derives quantifiable boundaries for optimal policy design.

Our primary conclusion is that optimal environmental policy is an exercise in strategic calibration, not unilateral maximization. We demonstrated conclusively that overly aggressive policies, while well-intentioned, can trigger a "crowding-out" effect on private R&D and create severe competitive distortions that penalize incumbent firms, ultimately undermining the financial stability of the market transition. The most effective policies are those that employ moderate, calibrated incentives to foster a balanced equilibrium, encouraging both innovation and strategic portfolio management.

From a managerial perspective, this study re-frames self-cannibalization from an unavoidable threat to an endogenous and manageable strategic cost. The findings provide a clear playbook for leaders of multi-product firms: a gradual, phased approach to GPD, coupled with adaptive dual-channel pricing and strategic product differentiation, is the optimal path to aligning ESG objectives with sustained profitability. This approach is central to modern sustainable supply chain management, where coordinating internal strategy with external policy is paramount (Taleizadeh et al., 2016).

While this model provides significant theoretical and practical insights, its limitations-namely the duopoly structure, linear demand assumptions, and absence of consumer heterogeneity-open promising avenues for future research. Extending this dynamic framework to oligopolistic markets, incorporating stochastic demand, and validating the findings with empirical case studies would further enrich our understanding of the complex journey toward a sustainable global economy. By bridging economic theory with actionable strategy, this study offers a robust foundation for designing more efficient policies and equipping firms with the tools to navigate the delicate balance between profitability and ecological stewardship.

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