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Environmental Policy Design in Green Product Development: Examining Cannibalization in Competitive Markets

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Abstract
This study develops a game-theoretic model to examine green product development (GPD) strategies in competitive markets, emphasizing trade-offs between innovation incentives, environmental policy interventions, and adaptive cannibalization strategies. Our findings indicate optimal government intervention can significantly enhance sustainable innovation, whereas overly aggressive interventions may diminish incentives. We reveal that strategic pricing can mitigate cannibalization effects while enhancing overall sustainability. These insights provide a theoretical foundation for effective environmental policy-making and practical strategies for firms navigating sustainability in competitive environments.

Keywords: Green Product Development (GPD); Environmental Policy Design; Market Competition; Cannibalization Strategy; Game Theory.

1. Introduction

The global imperative for sustainable production has catalyzed unprecedented policy responses, with 485 environmental instruments implemented across 62 countries between 2019–2022 [1]. This regulatory evolution, formalized through UN Resolution 77/162's Global Strategy for Sustainable Production [2], has positioned green product development (GPD) as a cornerstone of industrial transformation. Yet policymakers must reconcile multiple, often conflicting, objectives across economic, ecological, and social dimensions [3], striving to create coherent frameworks that effectively shape market behavior and drive sustainable transitions [4, 5].

Translating environmental policies into market outcomes remains complex. While Porter's Hypothesis contends that stringent environmental regulations can incentivize innovation [6], real-world applications reveal significant tensions between short-term costs and long-term benefits. Such misalignment underscores the fundamental challenge of designing policy mechanisms that bridge economic imperatives with environmental objectives. Beyond policy-market dynamics, the phenomenon of cannibalization—where new product launches erode sales of existing offerings—further complicates matters. For instance, Ford's eco-friendly Focus saw a 59.7% surge in sales but simultaneously cannibalized the firm's conventional Fiesta, which declined by 18% [7]. This illustrates how strategic product positioning can make cannibalization either a liability or a catalyst for market expansion.

Recent theoretical advances reveal deeper intricacies in sustainable market equilibria. Amiri, Alinaghian [8] show that heightened environmental consciousness can paradoxically hinder market outcomes if green product costs do not align with perceived consumer benefits. Similarly, Nike's Flyknit initiative underscores the structural hurdles in reconciling ambitious sustainability goals with actual market viability [9]. These findings point to the need for analytical frameworks that capture the endogenous interplay among policy interventions, competition, and cannibalization effects.

Against this backdrop, several fundamental questions arise:

1. How do regulatory frameworks and competitive dynamics interact in shaping firms' strategic behavior in GPD?
2. What mechanisms drive the equilibrium balance between cannibalization effects and market expansion in competitive green markets?

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3. How can policy interventions be optimally designed to foster sustainable innovation while preserving market efficiency?
4. What role do consumer environmental preferences and market sensitivities play in determining strategic equilibria?

To address these questions, we develop a game-theoretic framework examining strategic interactions between firms and regulatory bodies in green product markets. Our analysis advances understanding of the critical balance between competition, cannibalization, and environmental objectives in competitive environments, providing theoretical insights and practical implications for both firms and policymakers navigating sustainable transitions.

2. Literature Review

The literature on green product development (GPD) encompasses three interconnected research streams: the evolution and foundations of GPD, market competition and strategic considerations, and policy frameworks' interaction with market dynamics.

2.1. Foundations and Evolution of Green Product Development

Green product development has emerged as a strategic imperative driven by environmental regulations and evolving consumer preferences. Hojnik and Ruzzier [10] demonstrate that these dual pressures have accelerated innovations in energy-efficient technologies and sustainable manufacturing processes. The theoretical foundation of GPD is anchored in Porter's Hypothesis, which posits that well-designed environmental regulations catalyze innovation and enhance competitive performance [11]. This perspective is complemented by Elkington's Elkington [12] triple bottom line framework emphasizing the integration of economic, social, and environmental dimensions, further validated by contemporary research Mura, Longo [13].

Recent studies have identified self-cannibalization as a critical challenge in GPD implementation, where sustainable products potentially diminish demand for conventional offerings [8]. Strategic repositioning analyses, exemplified by Tesla's market approach [14], demonstrate how adaptive pricing and effective branding can mitigate these effects. Research on green product pricing strategies [15] underscores the need for quantitative models capturing the interplay between regulatory change, market demand, and technological innovation [16].

2.2. Market Competition and Strategic Considerations

The competitive dynamics of green markets present distinct challenges that transcend conventional industry concerns, particularly regarding strategic positioning and market sustainability. Huang, Mbanyele [17] demonstrate that green innovation initiatives incur substantial short-term profitability risks, especially in R&D-intensive sectors, where market uncertainties and capital requirements amplify these challenges. A critical strategic concern is self-cannibalization, where green product introductions can erode established conventional offerings [8]. This phenomenon is particularly evident in industries with high product substitutability and environmentally conscious consumers.

In response, firms have developed sophisticated strategic approaches. Market segmentation and adaptive pricing mechanisms enable strategic positioning of green products as either premium alternatives or sustainable substitutes [15]. These strategies employ dynamic pricing models responsive to consumer preferences, competitive pressures, and regulatory environments. Wagner, Velander [18] emphasize that effective implementation requires robust consumer behavior modeling and real-time market analytics, highlighting the critical balance between innovation-driven growth and financial performance.

2.3. Policy Frameworks and Market-Policy Integration

Government policy drives GPD through various instruments, from direct subsidies to comprehensive regulatory frameworks, with effectiveness varying across market contexts. Yang, He [19] document how targeted subsidies in China's renewable energy sector have catalyzed technological advancement, while [20] analyze the European Union's Circular Economy Action Plan's role in fostering sustainable production practices.

The influence of policy interventions on innovation exhibits complex dynamics. . Kneller and Manderson [21] demonstrate that overly rigid regulations can impose prohibitive compliance costs, diverting resources from R&D. Conversely, Jaffe, Newell [22] and Wang, Wan [23] argue that flexible regulatory approaches more effectively foster innovation while minimizing market distortions. Marrero, Baena [24] further emphasize the significance of political and social capital in policy effectiveness.

The market-policy interface requires careful consideration of multiple factors. Rennings [25] emphasizes policy effectiveness's context-dependency, while Callander, Foarta [26] demonstrate the necessity of industry-specific calibration. Chen, Yang [27] address temporal dimensions of policy implementation, and Bari, Chimhundu [28] and

Lazzarini [29] analyze variations across market structures, collectively highlighting the need for adaptive regulatory frameworks that accommodate diverse competitive environments.

Literature Review

Green Product Development (GPD) research is structured around three critical themes: (1) strategic foundations and market evolution, (2) competition and cannibalization in green markets, and (3) policy interventions shaping sustainable transitions.

1.1 Strategic Foundations and Market Evolution

GPD is increasingly driven by regulatory frameworks and shifting consumer demand for sustainable solutions [10]. Porter's Hypothesis suggests that well-designed environmental policies can spur innovation and enhance competitiveness [11]. The Triple Bottom Line framework further integrates economic, social, and environmental objectives, emphasizing the necessity of sustainability in industrial growth [12, 13].

However, self-cannibalization—where green products erode existing product sales—remains a core challenge [8]. Tesla's pricing and branding strategies illustrate how firms can strategically reposition green products to mitigate this effect while expanding market share [14]. Additionally, quantitative models are required to optimize pricing, competition strategies, and regulatory alignment [15, 16].

Market Competition and Cannibalization in Green Markets

The transition to sustainable markets presents profitability risks, especially in R&D-intensive industries where market uncertainty and investment costs are high {Huang, 2022 #19}. Additionally, green product introductions can lead to internal market cannibalization, particularly in sectors with high product substitutability and sustainability-conscious consumers [8].

To manage these challenges, firms adopt segmentation and adaptive pricing to position green products as premium alternatives or substitutes [15]. Real-time analytics further enhance strategic decision-making, optimizing pricing and differentiation [18].

Policy Interventions and Market-Policy Dynamics

Government interventions, including subsidies, carbon pricing, and regulatory incentives, play a decisive role in shaping green product adoption. For example, China's renewable energy subsidies have accelerated technological investment, while the EU's Circular Economy Action Plan has enhanced sustainable production frameworks [20].

The effectiveness of policy mechanisms varies. While rigid regulations can create cost burdens and deter R&D [21], flexible approaches encourage innovation with minimal market distortion [23]. Additionally, stakeholder engagement and political capital enhance policy effectiveness [24], while sector-specific regulatory designs and gradual policy transitions reduce market volatility and facilitate adaptation [26].

Despite extensive research, key gaps remain:

1. Limited understanding of the interplay between market competition, cannibalization, and policy interventions.
2. Insufficient modeling of phased policy implementations and firms' strategic adaptation.
3. Lack of theoretical models that quantify optimal regulatory thresholds for policy effectiveness.

To bridge these gaps, this study:

- Develops a game-theoretic framework that integrates competition, cannibalization, and policy interventions.
- Expands cannibalization theory, embedding self-cannibalization within firms' profit functions.
- Establishes analytical thresholds for optimal subsidy levels and policy interventions.

These contributions advance both theoretical and practical perspectives, offering insights into sustainable competition strategies while supporting policy-driven market transitions.

3. Research Scope and Problem Statement

The modern market landscape presents a strategic dilemma for firms balancing sustainability and profitability. As environmental concerns intensify, companies must develop eco-friendly products while sustaining financial performance. This study examines how two competing firms navigate strategic product development in a duopolistic market, influenced by consumer preferences, market dynamics, and government policies.

3.1. Market Evolution and Strategic Dynamics

Phase 1: Market Entry and Competitive Positioning

The market begins with Firm 1, an established player maintaining its traditional product line, and Firm 2, a challenger introducing an eco-friendly alternative. This direct competition between conventional and green products creates new market dynamics. Government subsidies and infrastructure investments play a critical role in incentivizing green adoption, while both firms adjust their strategies to shifting consumer preferences.

Phase 2: Market Expansion and Green Transition

As demand for sustainable products grows, Firm 1 enters the green segment, intensifying market competition. Now both firms must balance sustainability with legacy product management. Policy interventions and consumer demand evolution continue shaping the market, requiring firms to strategically allocate resources between traditional and sustainable product lines.

3.2. Key Market Influences

Government policies act as a catalyst for sustainable market transitions, using subsidies and infrastructure investments to promote green innovation while maintaining efficiency. Simultaneously, consumer preferences evolve, affecting price sensitivity, product expectations, and market share distribution between conventional and green offerings.

This study advances research by developing a game-theoretic framework that captures competitive interactions in green markets. We introduce new metrics to quantify cannibalization effects and integrate them into strategic decision-making models.

Our findings offer practical guidance for firms aiming to balance environmental responsibility with business sustainability. This analysis provides valuable insights for both industry leaders and policymakers, offering effective strategies for competitive advantage in transitioning markets.

4. 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
βc	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
γc	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	$MCI = MS^{k_2}/MS^{k_1} \geq 0$

4.1. 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:

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

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

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.

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.

Phase 1: Initial Market Dynamics

Social Welfare Impact ($gSWI_1$):

This function quantifies the overall societal benefit, encompassing consumer surplus and firm profits:

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

1. b) Environmental Impact (gEI1):

This function measures the environmental benefits derived from the adoption of green products:

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

2. 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 [30]. Strategic financial policies optimize the balance between profit-driven behavior and environmental sustainability through coordinated interactions among manufacturers, consumers, and regulatory frameworks [31] .The financial impact is expressed as:

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

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:

$$gSWI_2 = \sigma\left(\frac{(DN_1^2)^2 + (DG_1^2)^2 + (DG_2^2)^2}{2}\right) + \pi tF_1^2 + \pi F_2^2 \quad (15)$$

2. Environmental Impact (gEI2):

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.

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.

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: (18)

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

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

1. Market Capture Index (MCI)

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

$$MSF_1^1 = \frac{DN_1^1}{DN_1^1 + DG_2^1} \quad (19)$$

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

$$MSF_1^1 = \frac{DtF_1^2}{DtF_1^2 + DG_2^2} \quad (20)$$

The Market Capture Index compares market shares between phases:

$$MCI = \frac{MSF_1^2}{MSF_1^1} \quad (21)$$

- 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

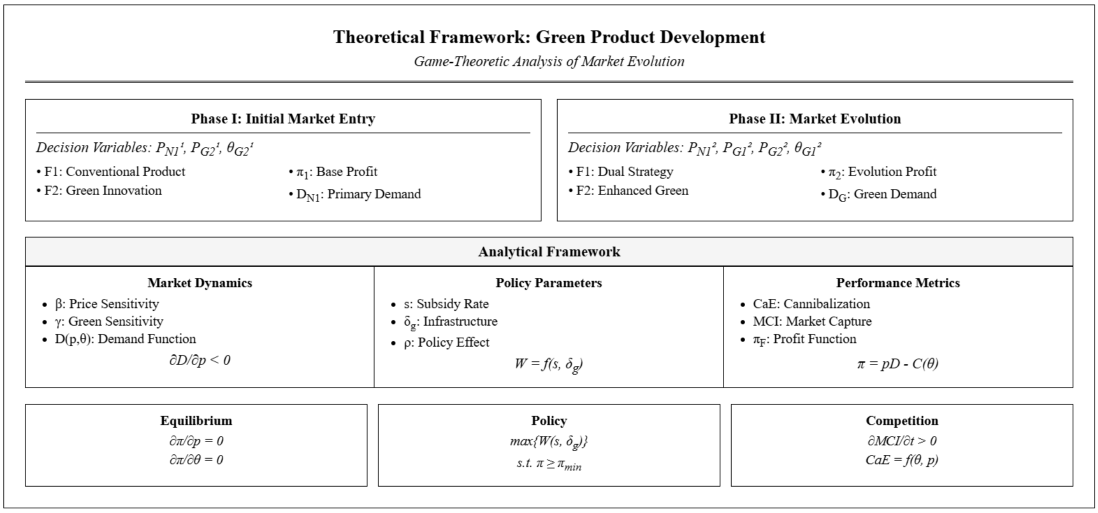


Figure 1. theorical framework and analytical framework of the considered problem on Green Product Development

5. 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.

Three-Stage Solution Process

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

5.1. 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

$$\frac{\partial \pi F_2^1}{\partial PG_2^1} = 0 \quad (22)$$

$$\frac{\partial \pi F_2^1}{\partial \theta G_2^1} = 0 \quad (23)$$

$$\frac{\partial \pi F_1^1}{\partial PN_1^1} = 0 \quad (24)$$

Solving the Nash game yields equilibrium values for firms' strategic pricing and greenness variables.

5.2. 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:

$$\frac{\partial \pi_t F_1^2}{\partial PG_1^2} = 0 \quad (25)$$

$$\frac{\partial \pi_t F_1^2}{\partial \theta G_1^2} = 0 \quad (26)$$

Phase 2 calculations incorporate Stage 1 equilibrium values to reflect competitive evolution in the expanded green market.

5.3. Stage 3: Government Policy Optimization

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

$$gPH_t = gPH_1 + gPH_2 \quad (27)$$

$$gPH_i = gSWI_i + gEI_i + gFI_i \quad (28)$$

Given the complexity, a combination of numerical optimization techniques and graphical analysis is employed:

1. Generate contour plots of the objective function over a range of values for s and δ.
2. Analyze these plots to identify regions of optimal policy combinations.
3. Fine-tune optimal values using Mathematica's optimization tools.

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: $DN_1^2 = \alpha - \beta_0 PN_1^2 + \beta_r PG_2^2 + \gamma_r \theta G_2^2$ $DG_2^2 = \alpha - \beta_0 PG_2^2 + \beta_r PN_1^2 + \gamma_0 \theta G_2^2$ • Profit Functions: $\pi N_1^2 = (PN_1^2 - cN)DN_1^2$ $\pi G_2^2 = (PG_2^2 - cG + s)DG_2^2 - \mu(\theta G_2^2)^2/2$	Variables: PN_1^{2*}, $\{PG_2^{2*}, \theta G_2^{2*}\}$ FOCs: $\partial \pi N_1^2/\partial PN_1^2 = 0$ $\partial \pi G_2^2/\partial PG_2^2 = 0$ $\partial \pi G_2^2/\partial \theta G_2^2 = 0$
Phase I (t = 1)	• Demand Functions: $DN_1^1 = \alpha - \beta_0 PN_1^1 + \beta_r PG_2^1 + \gamma_r \theta G_2^1$ $DG_2^1 = \alpha - \beta_0 PG_2^1 + \beta_r PN_1^1 + \gamma_0 \theta G_2^1$ • Profit Functions: $\pi N_1^1 = (PN_1^1 - cN)DN_1^1$ $\pi G_2^1 = (PG_2^1 - cG + s)DG_2^1 - \mu(\theta G_2^1)^2/2$	Variables: PN_1^{1*}, $\{PG_2^{1*}, \theta G_2^{1*}\}$ FOCs: $\partial \pi N_1^1/\partial PN_1^1 = 0$ $\partial \pi G_2^1/\partial PG_2^1 = 0$ $\partial \pi G_2^1/\partial \theta G_2^1 = 0$
Government (t = 0)	• Consumer Utility: $U = \alpha(DN_1^1 + DG_2^1 + DN_1^2 + DG_2^2) - \beta_0(DN_1^{12} + DG_2^{12} + DN_1^{22} + DG_2^{22})$ $+ \beta_r(DN_1^1 DG_2^1 + DN_1^2 DG_2^2) + \gamma_r(\theta G_2^1 DG_2^1 + \theta G_2^2 DG_2^2)$ • Consumer Surplus: $CS = U - (PN_1^1 DN_1^1 + PG_2^1 DG_2^1 + PN_1^2 DN_1^2 + PG_2^2 DG_2^2)$ • Social Welfare: $SW = CS + \pi N_1^1 + \pi N_1^2 + \pi G_2^1 + \pi G_2^2 - s(DG_2^1 + DG_2^2) - \delta$ • Environmental Impact: $EI = \theta G_2^1 DG_2^1 + \theta G_2^2 DG_2^2 \geq \bar{E}$ • Budget Constraint: $s(DG_2^1 + DG_2^2) + \delta \leq B$	Policy Variables: $\{s^*, \delta^*\}$ Optimization Problem: max SW s.t. $EI \geq \bar{E}$ s.t. $s(DG_2^1 + DG_2^2) + \delta \leq B$ s.t. $s, \delta \geq 0$

After completing 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:

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

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.

6. Numerical Analysis and Sensitivity Assessment: Examining Model Dynamics

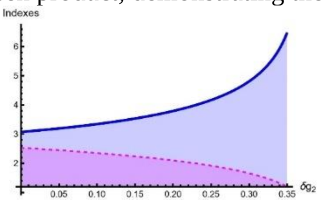
This section offers a numerical analysis of our Stackelberg game model, integrating theory with practical insights into GDP in competitive markets.

The analysis shows green product strategies must balance internal cannibalization, environmental impact, and regulatory compliance while meeting consumer demands for sustainability.

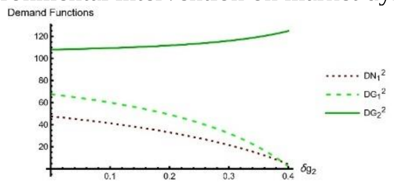
Parameter	α	β_o	β_r	β_c	γ_o	γ_r	γ_c	ζ
Value	100	0.99	0.41	0.05	0.06	0.05	0.04	0.05

Analysis of Strategic Variables and Functions in Relation to the Greenness investment by Government (δg_2)

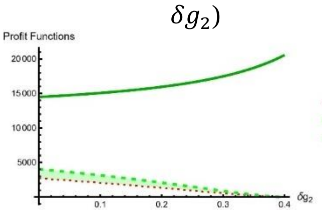
Figure 2 analyzes how government greenness investment (δg_2) affects four market variables: cannibalization and competition indexes, demand functions of both firms in phase 2, their respective profits, and the greenness degree of firm 1's green product, demonstrating the impact of government environmental intervention on market dynamics.



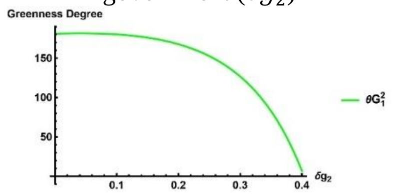
(a) Behavior of cannibalization and competition indexes regarding greenness investment by government δg_2)



(b) Behavior of demand functions of firm 1 and 2 products in phase 2, regarding greenness investment by government (δg_2)



(c) Behavior of profits stemming from firm 1 and 2 products in phase 2, regarding greenness investment by government (δg_2)



(d) Behavior of greenness degree of firm 1 green product in phase 2, regarding greenness investment by government (δg_2)

Figure 2 Behavior of a) cannibalization and competition indexes, b) demand functions, c) profits and d) greenness degree, regarding greenness investment by government (δg_2)

Figure 2(a) shows that the Market Capture Index (MCI) increases as government greenness investment (δg_2) rises, while the Cannibalization Effect (CaE) gradually declines. This indicates that government intervention reduces internal market competition and expands overall market potential.

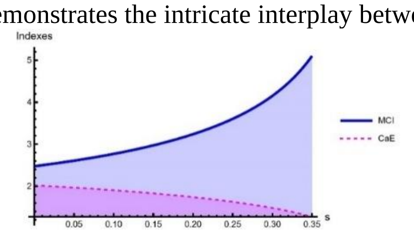
In Figure 2(b), demand functions reveal divergent trends: Firm 2's green product demand (DG_2^2) maintains and gradually increases its market position, while both Firm 1's conventional product demand (DN_1^2) and green product demand (DG_1^2) decline with increased government investment.

Figure 2(c) shows that Firm 2's green product profit (πG_2^2) positively correlates with government investment, while Firm 1's profits (πG_1^2 and πN_1^2) decline. This suggests that government intervention creates stronger competitive advantages for market leaders.

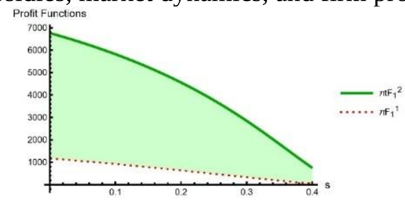
The greenness degree plot in Figure 2(d) reveals an inverse U-shaped relationship, where θG_1^2 initially increases with government investment but then sharply declines, indicating a complex interplay between public and private environmental investments.

Analysis of Strategic Variables and Functions in Relation to the Greenness Subsidy by Government

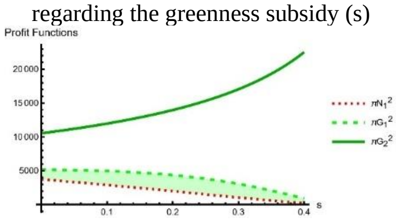
Figure 3. demonstrates the intricate interplay between government subsidies, market dynamics, and firm profitability.

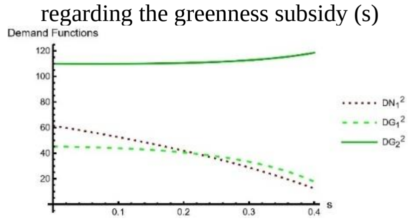


(a) Behavior of cannibalization and competition indexes, regarding the greenness subsidy (s)



(b) Behavior of firm1 profit functions in phase 1 and 2, regarding the greenness subsidy (s)





(c) Behavior of profit functions stemming from green and non-green product of firm 1 and 2 in phase 2, regarding the greenness subsidy (s)

(d) Behavior of demand functions stemming from green and non-green product of firm 1 and 2 in phase 2, regarding the greenness subsidy (s)

Figure 3 Behavior of a) cannibalization and competition indexes, b) and c) profit functions, d) demands and e) greenness degree, regarding the greenness subsidy (s)

The graphs in Figure 3(a) show that as the greenness subsidy (s) increases, the Market Capture Index (MCI) consistently rises while the Cannibalization Effect (CaE) gradually declines. This suggests that subsidies effectively expand market opportunities and reduce internal competition between product lines.

Figures 3(b) and (c) reveal contrasting profit patterns: Firm 2's green product profit (πG_2^2) grows strongly with increasing subsidies, while Firm 1's profits (πF_1^1 and $\pi t F_1^2$) decline. This indicates that subsidies provide stronger advantages for environmentally proactive firms.

Demand functions in Figure 3(d) illustrate that Firm 2's green product demand (DG_2^2) maintains steady growth with increasing subsidies, while demand for Firm 1's conventional (DN_1^2) and green products (DG_1^2) declines, suggesting that subsidies shift market share toward greener offerings.

The greenness degree plot indicates an inverted U-shaped relationship with subsidies, peaking at moderate levels and showing diminishing returns at higher levels.

These dynamics emphasize the need for effective coordination between private strategies and public policy, providing insights for corporate decision-makers and policymakers to promote sustainable market evolution while maximizing value and environmental impact.

7. Discussion

The findings of this study highlight the dynamic interdependence among green product development (GPD), cannibalization of existing product lines, and policy interventions in a competitive duopoly market. By modeling firm behavior across two phases—initial green product entry and broader green adoption—the research clarifies how market outcomes evolve when government incentives, consumer preferences, and competitive strategies intersect.

A key insight lies in the cannibalization trade-off. While introducing green products can diminish demand for a firm’s conventional offerings, well-crafted strategies-such as differentiated pricing, market segmentation, and timely introduction-can reduce the erosion of existing sales. These adaptive tactics allow incumbents to capture new consumer segments interested in sustainability, thereby transforming self-cannibalization from a threat into a growth opportunity. The analysis further indicates that late entrants can potentially learn from early movers, adjusting product attributes and pricing to capture under-served market niches.

From a policy standpoint, the study underscores that moderate, well-targeted government interventions (e.g., subsidies, infrastructure support) tend to enhance innovation incentives and expand the green product market. However, over-subsidization or rigid regulations may yield unintended effects, such as stifling competition or fostering complacency among early adopters. These findings align with the broader literature suggesting that flexible, performance-based policies can strike a balance between encouraging firms’ eco-innovation and preserving competitive market structures.

In terms of theoretical implications, integrating policy-driven market evolution and self-cannibalization in a game-theoretic framework extends current models of environmental economics and product-line design. The dual-phase approach, capturing both early adoption and subsequent market expansion, offers a richer understanding of how market equilibria evolve over time when both public and private stakeholders interact. This research thus contributes to the ongoing dialogue surrounding Porter’s Hypothesis, emphasizing that while regulatory support can foster environmental innovation, the intensity and structure of such support are pivotal to sustaining long-term competitive dynamics.

Finally, managerial implications center on how multi-product firms can manage the risk of internal demand shifts without sacrificing overall profitability. Investing in R&D for greenness and maintaining a strategic brand identity for new eco-friendly lines can secure competitive advantage in increasingly sustainability-driven markets. Nonetheless, anticipating future policy changes and adjusting product offerings accordingly remain critical. By bridging insights from corporate strategy and environmental policy, this discussion lays a foundation for firms and policymakers to jointly advance sustainable market transitions.

8. Conclusion

This study developed a game-theoretic model to examine how competing firms navigate green product development (GPD), considering the combined influences of government interventions, cannibalization risks, and competitive market dynamics. The results demonstrate that when policymakers strike a balance between moderate subsidies and infrastructure investments, green innovation can thrive without excessively distorting competitive forces. By contrast, overly generous incentives risk undermining firms' motivation to pursue ongoing R&D and eroding the profitability of conventional or late-adopting competitors.

From a managerial perspective, the analysis underscores the importance of strategic repositioning-particularly in pricing and segmentation-to mitigate the inherent challenges of self-cannibalization. Firms introducing green products must carefully align their offerings with evolving consumer preferences while anticipating shifts in regulatory support. Our findings highlight that well-timed, adaptive approaches can transform environmental responsibility from a cost burden into a differentiating factor, enhancing brand image and capturing emerging demand segments.

Notwithstanding its contributions, this model focuses on a duopolistic setting with two distinct phases of market evolution, implying that more complex, multi-firm contexts or international regulatory variations could yield further insights. Future research may also extend the framework to incorporate varying degrees of consumer heterogeneity, additional supply chain interactions, or empirical validation through real-world case studies. By bridging economic theory with sustainable innovation strategies, this study offers a foundation for designing more efficient policies and equipping firms with tools to navigate the delicate balance between profitability and environmental stewardship.

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