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Research on Evolutionary Game and Implementation Strategies for Promoting Near-Zero Energy Building Technologies

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Abstract

As a core decarbonization technology, the scaling up of Near-Zero Energy Building (NZEB) technologies under the “dual carbon” goal necessitates collaboration among governments, technology suppliers, and construction enterprises. However, high research and development (R&D) costs coupled with low market acceptance impede widespread adoption. This study develops a tripartite evolutionary game model to analyze strategic interactions among stakeholders. Using MATLAB 2022B simulations, we simulate the strategy sets for the government (subsidize/no subsidy), suppliers (R&D/no R&D), and enterprises (procure/no purchase). The results identify two Evolutionary Stable Strategies (ESS): a market-driven ESS (0, 1, 1) emerges when the green premium (P_m) exceeds the incremental cost (C_b); while a policy-driven ESS (1, 1, 1) requires government subsidies (S) to offset R&D gaps, specifically when $S > Cr/\alpha - P_m z$. These findings provide a theoretical basis for understanding the synergistic mechanisms underlying NZEB adoption and highlight the dynamic interplay between policy incentives and market forces.

Keywords: near-zero energy building technology; evolutionary game model; carbon reduction behavior; Matlab software simulation

1. Introduction

Against the backdrop of intensifying global climate change and the advancing implementation of China’s dual carbon strategy—specifically carbon peaking by 2030 and carbon neutrality by 2060—the building industry, as a primary sector for energy consumption and carbon emissions, is undergoing a critical transition toward green and low-carbon transformation, representing a crucial phase in achieving national strategic objectives. Recent statistics from the China Urban and Rural Construction Carbon Emissions Research Report (2024) indicate that lifecycle carbon emissions from the building sector account for 50.9% of the nation’s total carbon emissions, with building operations and material production contributing 21.7% and 28.0%, respectively [1]. Such a high-carbon emission profile underscores the pivotal role of the building industry in realizing the dual carbon targets. As a major technological innovation aimed at enhancing building energy efficiency, Near-Zero Energy Buildings (NZEBs) rely on advanced technological systems—such as high-performance envelopes, passive design strategies, and the integrated utilization of renewable energy sources—to substantially reduce operational energy consumption [2]. According to data from the Science and Technology Industrialization Development Center of the Ministry of Housing and Urban-Rural Development, NZEB demonstration projects achieve operational energy savings of 70–90% compared to national standards, demonstrat-



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ing considerable potential for energy conservation and emission reduction. This presents a viable technological pathway for the low-carbon transformation of the building industry.

Currently, the large-scale application of near-zero energy building (NZEB) technologies faces various practical challenges, which primarily manifest in three dimensions: technological, economic, and institutional systems. On the supply side, technology suppliers must allocate substantial financial resources to the development of novel materials (e.g., aerogel insulation panels and vacuum glazing) and system integration technologies [3]. Furthermore, they face significant risks, including protracted R&D cycles and insufficient technological maturity. These challenges are exacerbated by current market conditions characterized by high uncertainty regarding the correlation between innovation investment and anticipated returns, which ultimately discourages corporate R&D initiatives [4,5]. On the demand side, construction enterprises adopting NZEB technologies incur an implicit cost increase ranging from 15% to 30% [6]. Although these initial costs can be offset by long-term benefits—such as energy savings and policy incentives—they impose a considerable burden on enterprises' procurement decisions. Governments act as policy facilitators capable of promoting technology adoption through fiscal subsidies, tax incentives, and other regulatory instruments. Nevertheless, sustaining long-term, high-intensity subsidies is often infeasible due to budgetary constraints and regulatory limitations. Consequently, the inherent discrepancies in cost-benefit analysis, risk allocation, and policy expectations among these three stakeholders constitute the fundamental barrier hindering the widespread promotion of NZEB technologies.

Existing literature has made significant progress in optimizing technical parameters, conducting economic analyses, and formulating policies. However, several critical limitations remain evident. Primarily, much of the existing research relies on static analytical frameworks, which fail to adequately capture the dynamic strategic interactions and evolutionary processes among governments, technology suppliers, and construction enterprises during technology promotion. Furthermore, a notable deficiency lies in the lack of systematic quantitative analysis concerning critical parameters—such as subsidy intensity, R&D costs, and procurement intentions—often resulting in policy designs that lack precise empirical support. More importantly, existing studies have yet to establish an effective theoretical framework capable of simultaneously integrating the synergistic effects of technological maturity, market acceptance, and policy orientation.

Although the ecosystem for promoting NZEB technologies comprises a complex network of stakeholders—including developers, building owners, tenants, financial institutions, ESCOs, and certification bodies—this study specifically confines its scope to the tripartite nexus comprising the government, technology suppliers, and construction enterprises. This delimitation is predicated on a focused investigation into the micro-mechanisms of technology-policy interaction, deliberately excluding the broader financial and operational ecosystems.

Within the B2B context of construction technology diffusion, construction enterprises—functioning as either contractors or developers—serve as pivotal 'gatekeepers' responsible for final procurement decisions and the integration of technologies into projects. Consequently, the demand-side influences of developers, owners, and tenants are endogenized within the enterprise's payoff function through the market acceptance coefficient (β) and the green premium (Pm). Similarly, although financial institutions and ESCOs play critical roles in alleviating capital constraints, their functions are abstracted to preserve analytical tractability; consequently, financial risks are implicitly reflected in the R&D cost (Cr) and incremental cost (Cb) parameters. Furthermore, the regulatory functions of third-party certification bodies are subsumed under the government's enforcement mechanisms, as represented by the penalty terms (Fs , Fb). By internalizing these externalities, the model

avoids the complexity of multi-agent financial games, ensuring its focus remains on the core strategic interactions that drive technology adoption.

2. Literature Review

This chapter provides a systematic review of the existing literature across two principal domains: the current state of near-zero energy building (NZEB) technologies development and the application of evolutionary game theory within the field of building energy efficiency. The strategic interactions among multiple stakeholders are examined in the context of promoting NZEBs as a pivotal technological pathway for achieving energy conservation. Evolutionary game theory provides a robust methodological foundation for analyzing these strategic interactions. To address these gaps, a tripartite evolutionary game model involving the government, construction enterprises, and suppliers is developed, thereby offering a viable solution to the aforementioned research limitations.

2.1. Near-Zero Energy Building (NZEB) Technologies

Research on Near-Zero Energy Building (NZEB) technologies has progressed from single-parameter optimization to complex system integration. Foundational work by Chen Ping and Sun Cheng established a macro-level framework based on “passive priority and active optimization,” outlining a pathway for low-energy consumption coupled with high-generation capacity [7]. However, this model lacks a granular analysis of micro-parameter sensitivity across diverse climatic zones, limiting its applicability for localized implementation strategies. Addressing this gap, Feng Guohui et al. utilized the NSGA-II algorithm to perform multi-objective optimization of building envelopes in severe cold regions [8]. While this enhanced the scientific rigor of the design process, it failed to address the dynamic operational cost control issues that are critical prerequisites for formulating effective promotion strategies.

At the physical validation level, Kandilli and Gür advanced the state of the art through full-scale experimental studies. Kandilli verified the performance of a Composite Trombe Wall (CTW) utilizing zeolite–perlite composites, achieving a significant indoor-outdoor temperature differential of 11.97 °C [9]. Concurrently, Gür optimized a semi-transparent PV-integrated Double-Skin Façade (DSF), establishing a seasonally adaptive ventilation strategy (‘closed in winter, open in summer’) based on degree-hour integrals [10]. Despite these technical optimizations, both studies focused predominantly on technical feasibility, largely neglecting the variability in market acceptance under different economic incentive structures.

Techno-economic viability constitutes the core driver for large-scale promotion. Xu Wei et al. validated the compatibility between NZEB technologies and zero-carbon building roadmaps, quantifying that passive technologies account for 63% of incremental costs [11,12]. Building on this, Zou Fangrui et al. demonstrated the economic feasibility of a phased promotion approach through a case study of the Sino-Singapore Tianjin Eco-City [13]. Nevertheless, existing economic analyses are largely retrospective and static; they lack an examination of the game-theoretic behaviors of market participants—such as developers and residents—regarding cost allocation and benefit distribution. Similarly, while Shen Zenan advocated for climate-adaptive policy design, the discussion remains qualitative, lacking a quantitative assessment of how specific policy instruments incentivize regional industrial chain development [14].

Recent scholarship has increasingly incorporated social dimensions and intelligent controls. The “third pillar” theory proposed by Osama Omar—emphasizing user culture and social behavior—alongside Zhao Zefeng et al.’s analysis of regional climatic and economic heterogeneity, illuminates non-technical barriers to adoption [15,16]. These perspectives are technically complemented by Yushi Wang et al. on AI-driven energy

management and Eduardo Pierozan on the economics of retrofitting [17,18]. However, these studies typically treat technology, policy, and market dynamics as discrete silos, lacking a systematic modeling framework for the multi-party interaction mechanisms among “government-enterprise-user” stakeholders.

In summary, while the extant literature provides a robust foundation in technical and economic validation, significant gaps remain regarding multi-agent evolutionary game mechanisms, regionally tailored incentive policy design, and technology–market synergy strategies. Consequently, this paper employs evolutionary game theory to investigate the strategic choices and equilibrium conditions of stakeholders during the promotion of NZEB technologies, with the aim of providing a theoretical basis for formulating more adaptive implementation strategies.

2.2. Evolutionary Game Theory

When investigating the complex mechanisms underlying the promotion of Near-Zero Energy Building (NZEB) technologies, traditional static game models typically rely on assumptions of perfect rationality and symmetric information, thereby exhibiting significant limitations in explaining “market failures” driven by high transaction costs, information asymmetry, and bounded rationality. Static games typically treat key parameters—such as R&D costs and green premiums—as exogenous constants; consequently, they fail to capture the iterative learning processes among stakeholders. Furthermore, many existing models simplify the stakeholder structure to a binary government–enterprise interaction, thereby overlooking technology suppliers as independent strategic agents. Yet, supplier R&D efforts are crucial for enhancing technological maturity (α). In contrast, evolutionary game theory integrates the biological concept of “natural selection” into socioeconomic systems, thereby providing a more effective framework for simulating the long-term dynamic learning and strategy adjustment processes among governments, construction enterprises, and technology suppliers. Rather than presupposing an optimal solution, this approach employs replicator dynamic equations to delineate the system’s evolutionary trajectory over time, facilitating the identification of Evolutionarily Stable Strategies (ESS) and critical threshold conditions that induce spontaneous cooperation, thereby establishing a more realistic micro-theoretical foundation for analyzing the diffusion mechanisms of emerging NZEB technologies.

Early studies established foundational frameworks. Li et al. examined multi-agent interactions in recycling, identifying critical thresholds where subsidies offset cost increments [19]. However, this model lacks the specificity required for high-capital, long-cycle construction projects. Lv and Li introduced a tripartite model for NZEB technologies, identifying adoption thresholds and three-stage evolution [20]. Yet, their static threshold concept fails to capture dynamic cost reductions via technological learning.

Subsequent research expanded to financial and regulatory mechanisms. Zhang et al. integrated green finance into a tripartite game, highlighting synergy between policy and innovation [21]. Nevertheless, treating enterprises as homogeneous neglects size-based risk heterogeneity. Zhang Xia et al. focused on carbon markets, showing that excess quotas dilute incentives [22]. However, their “polluting enterprise” framework is ill-suited for the policy-driven construction sector. Lu Qiuqin et al. compared carbon regulatory tools, ranking dynamic regulation higher than taxes or penalties [23]. This conclusion, drawn from general industry, may not apply to construction, where penalties might stifle innovation.

Green building-specific studies introduced nuanced incentives. Liang Xi et al. optimized subsidy-tax mixes using utility and profit functions [24]. Still, they neglected the government’s reputational benefits (u_4), a key driver in Chinese policy contexts. Gao et al. advanced behavioral realism by embedding Prospect Theory into a government–ESCO–owner game,

capturing loss aversion and subjective risk weights [25]. While insightful for retrofits, this model excludes the complex developer–consumer–government triangle central to new NZEB technologies. Li et al. addressed regional industrial promotion, differentiating between SOEs and private firms based on real financial data [26]. Although they identified “fast/slow convergence zones,” their model did not quantify how specific NZEB technologies affect adoption utilities.

Recent work emphasizes systemic synergy. Ma et al. proposed an implicit “technology-space-behavior” co-evolution logic for campus planning [27]. However, the lack of a quantitative payoff matrix hinders policy translation. Zhao et al. made a significant contribution by proposing a “Technology-Reputation-Policy” synergy framework and calibrating it with Shenzhen/Beijing data [28]. They quantified the trade-off between subsidy phase-out and cost reduction (e.g., a 20 CNY/m² subsidy cut requires a 0.2% cost drop). Despite this rigor, the model assumes perfect rationality and uses a generic “price-cost increment” rather than specific NZEB technologies performance metrics (e.g., thermal storage efficiency).

In summary, although existing literature has made significant progress in constructing evolutionary game models, evaluating policy instruments, and incorporating behavioral factors, a notable knowledge gap persists within the specific domain of NZEB technologies. Few studies have systematically integrated the government, construction enterprises, and technology suppliers into a unified tripartite game framework. Specifically, in-depth quantitative research is lacking regarding the bidirectional interactions between technology suppliers’ R&D investment decisions and construction enterprises’ procurement decisions, as well as how government subsidies can be precisely targeted at this specific supply chain to synergize technology cost reduction and market expansion. Consequently, this paper seeks to develop an evolutionary game model encompassing these three stakeholders to bridge this theoretical gap and formulate strategic recommendations for the large-scale promotion of NZEB technologies.

3. Model Construction

This paper develops an evolutionary game model involving the government, suppliers, and construction enterprises as key players. The rationale for selecting this model is primarily twofold. First, evolutionary game theory relaxes the stringent assumption of perfect rationality inherent in classical game theory, accommodating instead the bounded rationality of stakeholders who adjust strategies through trial and error, imitation, and learning [29,30]. Second, multi-stakeholder interest games are intrinsic to the promotion of NZEB technologies, implying that the strategic decisions of all involved parties are interdependent. Limitations in information, resources, and cognitive abilities render decision-making a dynamic and incremental process [31]. Consequently, such multi-stage problems involving bounded rationality are best analyzed using evolutionary game theory.

3.1. Problem Description

As a fundamental decarbonization technology within the building industry, and bolstered by the dual carbon strategy (carbon peaking and carbon neutrality), NZEB technologies necessitate coordinated efforts from the government, suppliers, and construction enterprises to facilitate their widespread adoption. Figure 1 illustrates the evolutionary game relationship among the three participants. NZEB technologies can reduce operational carbon emissions by over 80% compared to conventional buildings, primarily through the integration of high-performance building envelopes and renewable energy systems. Nevertheless, in the early stages of implementation, NZEB technologies face significant barriers, including elevated R&D costs and limited market acceptance:

(1) Government: Although subsidies may be implemented to alleviate barriers to the adoption of NZEB technologies, their execution and sustainability are constrained by budgetary limitations.

(2) Suppliers: Research and development (R&D) of NZEB technologies entails substantial investment and carries the inherent risk of failure.

(3) Construction Enterprises: The adoption of NZEB technologies incurs an initial cost premium (e.g., a 15–30% technology premium), which can be offset by policy incentives (e.g., credits under green building certification programs) and long-term cost savings (e.g., reducing energy consumption by 30–50%).

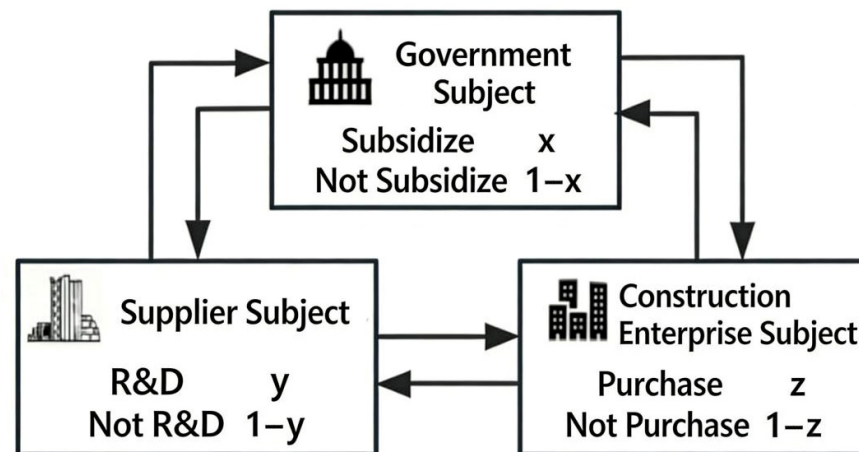


Figure 1. Tripartite evolutionary game relationship.

3.2. Parameter Setting

3.2.1. Agent Assumptions

(1) The government determines the promotion of NZEB technologies through the decision of whether to introduce subsidies.

(2) Suppliers choose between investing in NZEB technologies R&D or adhering to traditional technology development methods.

(3) Construction enterprises decide whether to procure NZEB technologies or opt for traditional alternatives.

3.2.2. Key Assumptions

(1) Bounded Rationality: Under bounded rationality, the three parties cannot perfectly predict each other's actions; consequently, they adjust their strategies based on past experiences, reflecting the real-world constraints of limited information and cognitive capacity.

(2) Policy Targeting: Only suppliers who adopt NZEB technologies receive government subsidies—which incentivize R&D—whereas sanctions are imposed exclusively on non-conforming parties that neither adopt the technology nor procure it.

(3) Cost Correlation: The cost of NZEB technologies—specifically the supplier's R&D cost, C_r —decreases with the maturation coefficient, α , according to $C_r = C_{r0}/\alpha$, where C_{r0} denotes the initial R&D cost.

(4) Benefit Symmetry: Long-run benefits derived from construction enterprises adopting NZEB technologies are discounted to their present value. Given the complexity of intertemporal calculations, this assumption simplifies the model.

(5) Market Equilibrium: The theory assumes that NZEB technologies and conventional alternatives are functionally equivalent, differing only in cost and environmental attributes. Consequently, the cost–benefit ratio serves as the sole determinant in construction enterprises' procurement decisions.

Table 1 presents the notations and definitions for all model parameters.

Table 1. Parameter Symbols and Their Meanings.

Symbol	Type	Meaning	Value Range
x	Government Strategy	Probability of the government subsidizing ($1 - x$ represents the probability of no procurement)	$x \in [0, 1]$
y	Supplier Strategy	Probability of the supplier investing in R&D for NZEB technologies ($1 - y$ represents the probability of no R&D investment)	$y \in [0, 1]$
z	Construction Enterprise Strategy	Probability of the enterprise procuring ($1 - z$ represents the probability of no procurement)	$z \in [0, 1]$
S	Government Parameter	Per-unit subsidy for materials provided to suppliers (RMB)	$S > 0$
Cr	Supplier Parameter	Fixed R&D and production costs for NZEB technologies (monetary units)	$Cr > 0$
Pm	Market Parameter	Green premium for NZEB technologies (RMB per unit, defined as the additional payment made by the purchaser)	$Pm > 0$
Cb	Construction Enterprise Parameter	Incremental procurement cost for enterprises adopting NZEB technologies (covering price premium and associated costs; monetary units per unit)	$Cb > 0$
Re	Government Parameter	Long-term environmental governance revenue accruing to the government per unit of procured NZEB technologies, scaled by the procurement probability z (monetary units)	$Re > 0$
Fs	Penalty Parameter	Fine imposed by the government on a non-compliant supplier (per unit of material, monetary units)	$Fs > 0$
Fb	Penalty Parameter	Fine imposed by the government on a non-compliant construction enterprise (per unit of material, monetary units)	$Fb > 0$
α	Technology Parameter	Technological maturity coefficient ($\alpha > 1$ indicates higher maturity, leading to reduced R&D costs per unit)	$\alpha > 1$
β	Market Parameter	Market acceptance coefficient ($\beta \in [0, 1]$) modulating the effective green premium ($Pm\beta$), where a higher value indicates greater market realization of the premium	$\beta \in [0, 1]$

4. Evolutionary Game Analysis

4.1. Expected Payoffs of the Three Participating Parties

The payoffs for the three parties are determined by their strategic combinations (government: x , supplier: y , construction enterprise: z). Consequently, a payoff matrix is constructed to calculate the expected returns.

4.1.1. Government's Expected Profit

The government's objective is to maximize total social benefits, which comprise three core components. First, the environmental governance revenue, denoted as Rez , constitutes the long-term utility (carbon reduction) derived from the adoption of NZEB technologies, which is contingent on the construction enterprise's procurement probability z . Second, the subsidy expenditure, denoted as Sy , is incurred when the supplier invests in R&D for NZEB technologies (with probability y), necessitating a unit subsidy S paid by the government. Third, the penalty income, denoted as $Fs(1 - y)z + Fby(1 - z)$, is collected from non-compliant parties.

The government's expected payoff when choosing to subsidize (with probability x) is denoted as $Ug1$:

$$Ug1 = Rez - Sy + Fs(1 - y)z + Fby(1 - z) \quad (1)$$

The government's expected payoff when choosing not to subsidize (with probability $1 - x$) is denoted as $Ug2$:

$$Ug2 = Rez + Fs(1 - y)z + Fby(1 - z) \quad (2)$$

The government's average expected payoff in generation t , denoted as $Ug(t)$:

$$Ug(t) = xUg1 + (1 - x)Ug2 = Rez + Fs(1 - y)z + Fby(1 - z) + x(-Sy) \quad (3)$$

Crucially, the government's strategy evolution is driven by the net payoff differential between subsidizing and not subsidizing. Even when the subsidy amount S is zero, the government retains a strategic preference. If the environmental benefit Re and penalty revenues Fs, Fb are substantial, the payoff of not subsidizing—comprising only penalties and benefits without costs—can still be less than that of subsidizing, which includes benefits plus potential market stimulation, contingent on the values of y and z . Consequently, x can evolve towards 1 even in the absence of financial subsidies, signifying a transition to a “Regulatory-Driven” mode rather than a “Subsidy-Driven” mode.

4.1.2. Supplier's Expected Profit

The supplier's payoff comprises sales revenue, R&D costs, and penalty expenditures. Sales revenue is adjusted by the market acceptance coefficient β , such that the effective revenue becomes $Pm\beta$. This indicates that the unit price premium is fully realized only under high market acceptance and is earned solely when the construction enterprise procures the technology (with probability z). R&D costs are incurred only when the supplier invests in R&D for NZEB technologies (with probability y), requiring payment of an allocated cost Cr/α (where $\alpha > 1$ is the technology maturity coefficient that reduces R&D costs as it increases). Penalty expenditures occur only if the supplier does not invest in R&D ($1 - y$) but the construction enterprise still procures the technology (z), in which case the supplier must pay a government penalty Fs .

The supplier's expected payoff when investing in R&D for NZEB technologies (with probability y) is denoted as $Us1$:

$$Us1 = Pm\beta z - Cr/\alpha y - Fs(1 - y)z \quad (4)$$

The supplier's expected payoff when not investing in R&D for NZEB technologies (with probability $1 - y$) is denoted as $Us2$:

$$Us2 = 0 - Fs(1 - y)z \quad (5)$$

(no sales revenue or R&D costs, but a penalty may be incurred)

The supplier's average expected payoff in generation t , denoted as $Us(t)$:

$$Us(t) = yUs1 + (1 - y)Us2 = y(Pm\beta z - Cr/\alpha y - Fs(1 - y)z) + (1 - y)(-Fs(1 - y)z) \quad (6)$$

4.1.3. Construction Enterprise's Expected Profit

The payoff of the construction enterprise comprises procurement benefits, initial costs, and penalty expenditures. Procurement benefits are realized only when the supplier invests in R&D for NZEB technologies (with probability y), where the construction enterprise obtains a unit price premium Pm (achieved through policy incentives or energy-saving benefits). Initial costs are incurred only if the construction enterprise procures the technology (with probability z), necessitating payment of a unit cost increment Cb (representing the price difference between NZEB technologies and conventional technologies). Penalty expenditures occur only when the construction enterprise does not procure the technology ($1 - z$) but the supplier invests in R&D for NZEB technologies (y), in which case the construction enterprise must pay a government penalty Fb .

The expected payoff for a construction enterprise when procuring (with probability z) is denoted as $Ub1$:

$$Ub1 = Pmy - Cbz - Fb(1 - z)y \quad (7)$$

The expected payoff for a construction enterprise when not procuring (with probability $1 - z$) is denoted as $Ub2$:

$$Ub2 = 0 - Fb(1 - z)y \quad (8)$$

(no procurement cost or benefit, but a penalty may be incurred).

The average expected payoff for the construction enterprise, denoted as $Ub(t)$:

$$Ub(t) = zUb1 + (1 - z)Ub2 = z(Pmy - Cbz - Fb(1 - z)y) + (1 - z)(-Fb(1 - z)y) \quad (9)$$

According to evolutionary game theory, the growth rate of a strategy is proportional to the difference between its expected payoff and the population's average expected payoff.

Government replicator dynamic equation $Fg(x)$:

$$Fg(x) = x(Ug1 - Ug(t)) \quad (10)$$

$$Fg(x) = xSy(x - 1) = -Syx(1 - x) \quad (11)$$

Supplier replicator dynamic equation $Fs(y)$:

$$Fs(y) = y(Us1 - Us(t)) \quad (12)$$

$$Fs(y) = y(1 - y)(Pm\beta z - Cr/\alpha y) \quad (13)$$

Construction enterprise replicator dynamic equation $Fb(z)$:

$$Fb(z) = z(Ub1 - Ub(t)) \quad (14)$$

$$Fb(z) = z(1 - z)(Pmy - Cbz) \quad (15)$$

4.2. Jacobian Matrix Derivation and Evolutionary Stable Strategy (ESS) Analysis

4.2.1. Jacobian Matrix Derivation

$$Fg(x) = -Syx(1 - x) \quad (16)$$

$$Fs(y) = y(1 - y)(Pm\beta z - Cr/\alpha y) \quad (17)$$

$$Fb(z) = z(1 - z)(Pmy - Cbz) \quad (18)$$

$$J = \begin{matrix} \frac{\partial Fg}{\partial x} & \frac{\partial Fg}{\partial y} & \frac{\partial Fg}{\partial z} \\ \frac{\partial Fs}{\partial x} & \frac{\partial Fs}{\partial y} & \frac{\partial Fs}{\partial z} \\ \frac{\partial Fb}{\partial x} & \frac{\partial Fb}{\partial y} & \frac{\partial Fb}{\partial z} \end{matrix} \quad (19)$$

Substituting the aforementioned formulas yields the final Jacobian matrix as follows:

$$J = \begin{matrix} -Sy(1 - 2x) & -Sx(1 - x) & 0 \\ 0 & Pm\beta z(1 - 2y) - y(1 - y)\frac{Cr}{\alpha} & y(1 - y)Pm \\ 0 & z(1 - z)Pm & Pmy(1 - 2z) - z(1 - z)Cb \end{matrix} \quad (20)$$

4.2.2. Global Equilibrium Points and Stability Analysis

(1) Global Equilibrium Points

To comprehensively evaluate the system's evolutionary stability, it is essential to analyze the eigenvalues across all eight vertices of the unit cube. By substituting the equilibrium points (x^*, y^*, z^*) into the Jacobian matrix J —derived from the replicator

dynamic equations—we assess the signs of the eigenvalues for each point. The detailed results are summarized in Table 2.

Table 2. Global Equilibrium Points Analysis.

No.	Equilibrium Point (x, y, z)	Eigenvalues ($\lambda_1, \lambda_2, \lambda_3$)	Stability Determination	Description of System State
1	(0, 0, 0)	0, 0, 0	Unstable/Neutral	Zero matrix; linearization fails. Conditionally stable (risk-dominant stagnation) if $S < Cr/\alpha$ and $Pm < Cb$; not asymptotically stable.
2	(0, 0, 1)	0, Pm , 0	Unstable	Saddle point; positive eigenvalue ($Pm > 0$). Suppliers inevitably evolve toward R&D given market premium without subsidy; state is unsustainable.
3	(0, 1, 0)	0, $-Pm$, Pm	Unstable	Contradictory state; positive eigenvalue ($Pm > 0$). Construction enterprises will not maintain ‘non-procurement’ strategy given benefits without penalty pressure.
4	(0, 1, 1)	0, $-Pm$, $-Pm$	Stable (ESS)	Market-driven ESS; negative non-zero eigenvalues. Market mechanism spontaneously forms ‘R&D-procurement’ closed loop when $Pm > Cb$ and technology is mature; no government intervention required.
5	(1, 0, 0)	$-S$, 0, 0	Unstable	Resource waste; zero eigenvalue exists. Unilateral subsidies without supply–demand response; fiscal pressure forces strategy reversal.
6	(1, 0, 1)	$-S$, Pm , $-Cb$	Unstable	Supply–demand disconnection; positive eigenvalue ($Pm > 0$). Suppliers face contradiction with procurement but insufficient returns ($Pm < Cr/\alpha$); strategy is unstable.
7	(1, 1, 0)	$-S$, Cr/α , Cb	Unstable	Compulsory failure; positive eigenvalue ($Cb > 0$). Enterprises face ‘high-cost, no-benefit’ dilemma; inevitable exit.
8	(1, 1, 1)	S , Pm , $-Cb$	Conditionally Stable	Policy-driven Synergy: Eigenvalue $S > 0$ indicates a mathematical Repeller. Stability depends on specific parameter space constraints (see discussion below).

An ESS must satisfy two conditions. First, at the equilibrium point, the replicator dynamic equations for all strategic variables must equal zero (Nash Equilibrium). Second, the real parts of all eigenvalues of the Jacobian matrix—evaluated at that equilibrium point—must be negative (local asymptotic stability). Based on the eigenvalue analysis in Table 2, the system possesses an Evolutionary Stable Strategy (ESS) only under specific parametric conditions. Notably, while the mathematical criterion for local asymptotic stability requires all eigenvalues to have negative real parts, the actual convergence of the system in the game context must be determined by considering parameter thresholds.

(2) Stability Verification of Typical Equilibrium Points

Equilibrium point 1: (0, 0, 0): In this scenario, none of the three parties has an incentive to cooperate (when $S < Cr/\alpha$ and $Pm < Cb$).

$$\text{Jacobian matrix } J = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (21)$$

Computing the eigenvalues of the Jacobian matrix yields all zeros (a degenerate case). Consequently, this point represents a ‘risk-dominant’ equilibrium—a stable state in the absence of cooperation—provided that $S < Cr/\alpha$ and $Pm < Cb$.

Equilibrium point 2: (0, 0, 1): The government does not subsidize, the supplier does not engage in R&D, and the construction enterprise procures NZEB technologies—a logical contradiction, as procurement is impossible without supplier R&D.

$$\text{Jacobian matrix } J = \begin{pmatrix} 0 & 0 & 0 \\ 0 & Pm & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (22)$$

Calculating the eigenvalues of the Jacobian matrix yields 0, Pm , 0 (where $Pm > 0$). Thus, this point is unstable due to the presence of a positive eigenvalue.

Equilibrium point 3: (0, 1, 0): In this case, the government does not subsidize, the supplier engages in R&D, and the construction enterprise does not procure the technology—a logical contradiction, as procurement is necessary to realize benefits when the supplier conducts R&D.

$$\text{Jacobian matrix } J = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & Pm \end{pmatrix} \quad (23)$$

Calculating the eigenvalues of the Jacobian matrix yields 0, 0, Pm (where $Pm > 0$). Since a positive eigenvalue exists, this point is unstable.

Equilibrium point 4: (0, 1, 1): In this scenario, the government does not subsidize, the supplier engages in R&D, and the construction enterprise procures—representing a market-driven spontaneous cooperation.

$$\text{Jacobian matrix } J = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -Pm & 0 \\ 0 & 0 & -Pm \end{pmatrix} \quad (24)$$

When the market premium for NZEB technologies (Pm) sufficiently offsets the incremental cost (Cb) for construction enterprises (i.e., $Pm > Cb$), and suppliers remain profitable absent subsidies, the eigenvalues become non-positive, driving the system toward spontaneous cooperation. Consequently, the government can refrain from intervention ($x = 0$), allowing market mechanisms to dictate the evolutionary process.

Equilibrium point 5: (1, 1, 1): In this case, the government provides subsidies, the supplier engages in R&D, and the construction enterprise procures NZEB technologies—representing a policy-driven collaborative cooperation.

$$\text{Jacobian matrix } J = \begin{pmatrix} S & 0 & 0 \\ 0 & -Pm & 0 \\ 0 & 0 & -Pm \end{pmatrix} \quad (25)$$

From the perspective of dynamical systems theory and parameter dependence, the ‘stability’ of (1, 1, 1) represents a controlled convergence path. The system evolves toward this equilibrium only when the benefits for the government, suppliers, and enterprises satisfy specific synergistic conditions:

Government Side: Subsidy costs must be less than total social benefits (environmental benefits + penalty revenue).

Supply Side: Government subsidies (S) must bridge the R&D cost gap (i.e., $S > Cr/\alpha - Pmz$).

Demand side: The comprehensive benefits for enterprises (market premium + energy-saving benefits – penalty risk) must be positive (i.e., $Pmy > Cb$).

Only when these synergistic conditions are met simultaneously will the system trajectories be confined to (1, 1, 1) within the bounded strategy space, resulting in a state of ‘bounded stability’ or ‘strategy locking,’ despite the presence of positive eigenvalues in the mathematical analysis.

5. Numerical Simulation

Utilizing MATLAB, we conduct simulations to analyze the dynamic process of strategy evolution among the government, suppliers, and construction enterprises under varying initial conditions. Based on the simulation results, we discuss the impacts of government subsidies, the intensity of rewards and penalties, and variations in the benefits for suppliers and construction enterprises [32,33]. Therefore, the baseline scenario is set as follows: $S = 0.5$, $Pm = 0.8$, $Cr/a = 0.6$, $Cb = 0.4$.

5.1. Impact of Changes in the Initial Probability x of Government Subsidy

Figure 2 illustrates the simulation results, demonstrating the impact of the government’s initial propensity (x) on the evolutionary trajectories of suppliers and construction enterprises, assuming other parameters remain constant. When the government’s initial propensity is low ($x = 0.2$), the probability of government intervention gradually increases over time, eventually converging to 1. This evolution occurs because, even in the absence of substantial fiscal subsidies, the government is driven by potential environmental benefits (Re) and penalty revenues (Fs, Fb). The government’s regulatory role—distinct from mere financial expenditure—generates a positive payoff differential that compels the strategy x to rise.

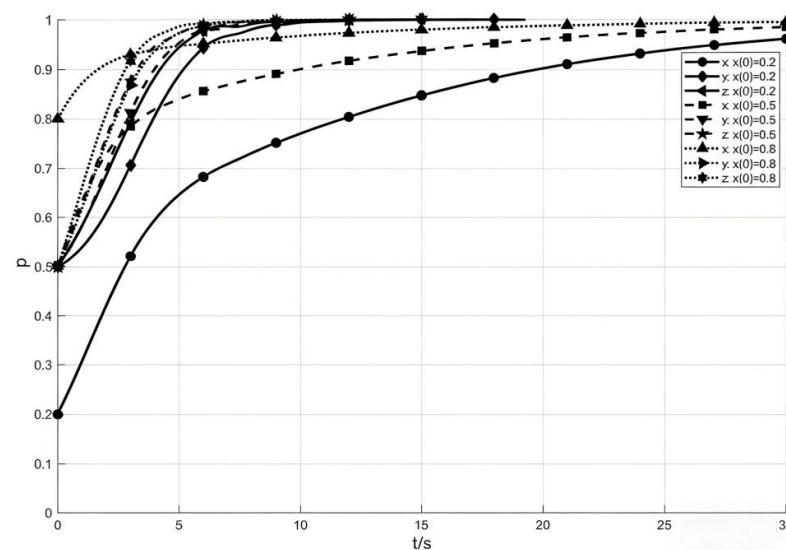


Figure 2. Evolutionary results of changes in the government’s initial willingness x .

As the government’s regulatory propensity (x) strengthens, it exerts a guiding effect on the market. Under the initial condition ($x = 0.2$), the willingness of suppliers and construction enterprises is initially hesitant. As shown in Figure 2, the probability of suppliers investing in R&D initially declines due to cost concerns before rebounding as government pressure mounts. In contrast, construction enterprises exhibit a rapid upward trend in procurement willingness, driven by the fear of penalties and the market premium. Ultimately, the system reaches a stable equilibrium at (1, 1, 1). This outcome confirms that the government’s active regulation—manifested through both subsidy mechanisms and penalty enforcement—can effectively overcome the initial inertia of suppliers and enterprises, locking the system into a state of full cooperation.

5.2. Impact of Changes in the Initial Probability y of Supplier Investment in R&D for Near-Zero Energy Building Technology

Figure 3 illustrates the evolutionary trajectories under different initial propensities of suppliers to engage in R&D (y). The simulation demonstrates that while the initial value of y does not affect the final equilibrium state of the system (where $x = 1, z = 1$), it significantly affects the convergence speed of both the government's subsidy strategy (x) and the construction enterprise's procurement strategy (z). Specifically, a higher initial propensity of suppliers to engage in R&D accelerates the convergence of all parties towards the optimal state.

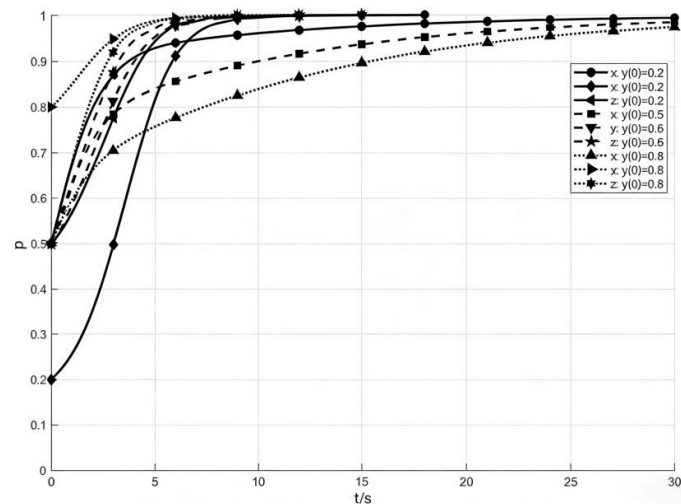


Figure 3. Evolutionary results of changes in the supplier's initial willingness y .

This phenomenon is attributable to the causal mechanism embedded in the replicator dynamic equations. As per Equation (15), the construction enterprise's decision to adopt (z) is directly dependent on the probability of the supplier providing the technology (y), since the payoff differential includes the term $Pm\beta y$. Consequently, a higher initial y directly increases the marginal payoff for the enterprise, serving as a primary catalyst that accelerates the convergence of z . In turn, this accelerated market activity—stemming from the supplier's initiative—modifies the government's cost-benefit calculation, thereby expediting the convergence of the subsidy strategy (x). Thus, while the supplier's R&D serves as the fundamental enabler for enterprise adoption, the government's response is a derivative response to the momentum established in the supply and demand market.

5.3. Impact of Changes in the Initial Probability z of Construction Enterprises Procuring Near-Zero Energy Building Technology

Figure 4 demonstrates how variations in the initial propensity of construction enterprises to procure (z) influence the evolutionary trajectories of the government and suppliers. Analogous to the effect of y , the initial value of z does not alter the final Evolutionary Stable Strategy (ESS) of the system, which remains at the ideal point (1, 1, 1). However, it is instrumental in determining the convergence speed of the supplier's R&D strategy (y) and, to a lesser extent, the government's subsidy strategy (x).

The underlying mechanism is driven by market feedback. As per Equation (13) ($F_s(y) = y(1 - y)(Pm\beta z - Cr/\alpha y)$), the supplier's incentive to invest in R&D is directly proportional to the market acceptance probability (z). When the initial propensity of enterprises to procure (z) is high (e.g., $z = 0.8$), the term $Pm\beta z$ in the supplier's payoff function increases significantly. This creates a strong 'pull' effect, wherein the anticipation of market demand accelerates the supplier's decision-making process regarding innovation.

Conversely, when z is low (e.g., $z = 0.5$), suppliers face greater market uncertainty, thereby slowing down their evolutionary pace. This delay in the supply response subsequently affects the timing of government intervention, as the government's incentive to subsidize is often contingent upon the existence of a viable supply–demand chain. Therefore, while government policy provides the regulatory framework, it is the enterprise's demand (z) that serves as the primary catalyst for technological supply.

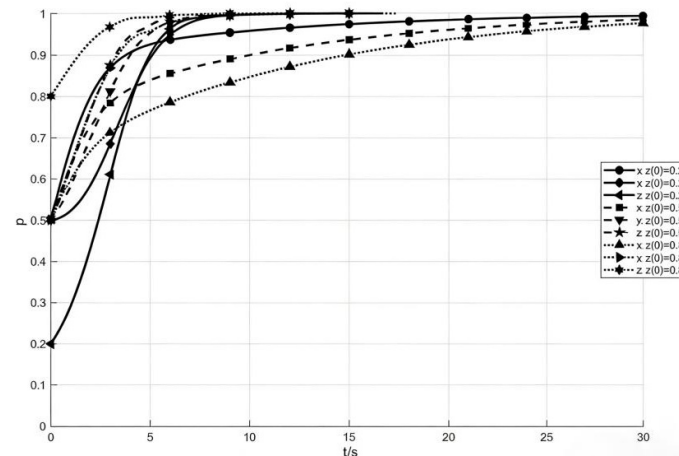


Figure 4. Evolutionary outcomes of changes in the initial willingness z of construction enterprises.

5.4. Impact of Changes in Government Subsidy Intensity S

Figure 5 illustrates the effect of subsidy intensity (S) on the system's evolution. A key finding is that the absence of subsidies ($S = 0$) does not halt the evolutionary process. In this scenario, the government retains a propensity to regulate ($x \rightarrow 1$), driven by environmental benefits and penalties, effectively managing the market without financial expenditure. Consequently, suppliers and enterprises still converge to cooperation, albeit at a slower pace.

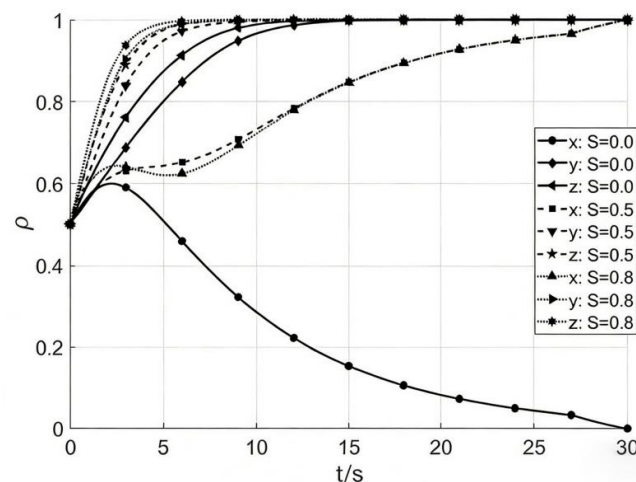


Figure 5. Evolutionary outcomes of changes in government subsidy intensity S .

However, increasing the subsidy intensity (S) serves as a catalyst. Higher subsidies improve the government's payoff for intervention, accelerating the convergence of x to 1. This rapid shift in government strategy significantly lowers the perceived risk for suppliers and enterprises, creating a positive feedback loop that drives the system to the ideal equilibrium (1, 1, 1) significantly faster than market forces alone.

5.5. Impact of Changes in the Initial Cost C_b of Construction Enterprises

Figure 6 illustrates the impact of varying the incremental initial cost (C_b) for construction firms procuring NZEB technologies on the strategies of the government and suppliers, with other parameters held constant. When the incremental initial cost for construction enterprises to procure NZEB technologies is relatively low ($C_b = 0.2$), as illustrated in Figure 6, the probabilities of the government subsidizing (x), suppliers investing in R&D (y), and enterprises procuring the technology (z) rise at the fastest rate, rapidly converging to the stable equilibrium (1, 1, 1). This indicates that low incremental costs for enterprises facilitate the establishment of a positive transmission chain linking subsidies, production, and procurement.

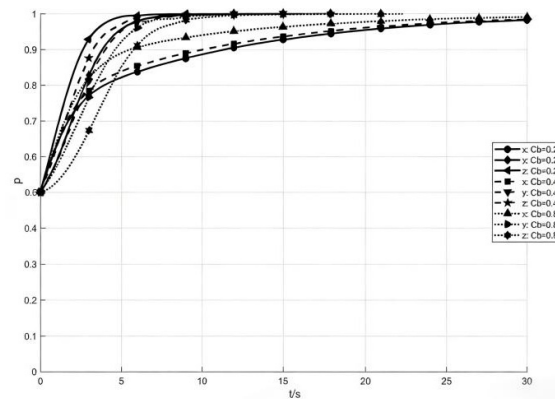


Figure 6. Evolutionary Results of Changes in the Initial Cost of Construction Enterprises C_b .

The evolutionary speeds of the government's subsidy strategy (x), the supplier's R&D strategy (y), and the enterprise's procurement strategy (z) are decreasing functions of the incremental initial cost (C_b), although all approach the stable equilibrium over time. Regardless of the level of initial cost, construction enterprises are inclined to reach a mature stage in the long run. The initial cost does not alter the endpoint of the evolution; rather, it only influences the speed at which the equilibrium is attained. This S-shaped growth pattern, characteristic of the evolutionary process, reflects the system's natural tendency to transition from disorder to order and from fluctuation to stability.

5.6. Impact of Changes in the Market Premium P_m of Low-Carbon Technology

Figure 7 illustrates the impact of the market premium (P_m) on the strategies of the supplier, construction enterprise, and government, with other parameters held constant. In Figure 7, under the low market premium scenario ($P_m = 0.3$), the low premium suppresses the probability of the supplier investing in R&D for NZEB technologies (y), and consequently, the probability of the construction enterprise procuring the technology (z) remains low. The lack of strong adoption willingness from both the enterprise and the supplier diminishes the government's motivation to subsidize. This drives the system towards the equilibrium point (0, 0, 0) in the long run, where the likelihood of the government subsidizing (x), the supplier investing in R&D (y), and the enterprise procuring the technology (z) all converge to zero.

At a moderate market premium for NZEB technologies ($P_m = 0.6$), the increased premium raises the likelihood of the supplier investing in R&D (y), which initially fluctuates before rising steadily; consequently, the likelihood of the construction enterprise procuring the technology (z) also increases steadily. During this process, the likelihood of government subsidy (x)—acting as a guiding mechanism—also rises to 1, establishing a stable state of production-procurement equilibrium.

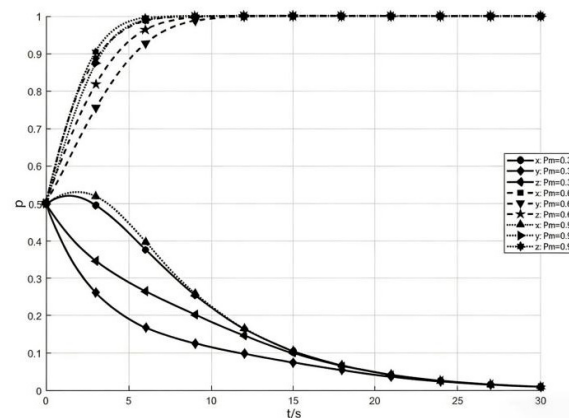


Figure 7. Evolutionary outcomes of changes in the market premium P_m of low-carbon technology.

In the high market premium scenario for NZEB technologies ($P_m = 0.9$), the probability of government subsidy (x) converges to 0, whereas the probabilities of the supplier engaging in R&D (y) and the enterprise procuring the technology (z) rise sharply and converge to 1. In this case, the high market premium enables collaboration between the supplier and the construction enterprise without government subsidies, driven by the spontaneous pursuit of economic returns in the NZEB market.

5.7. Impact of Changes in the Supplier's R&D Cost Cr/α

In Figure 8, the effect of changes in the supplier's R&D cost (Cr/α) on the participation strategies of construction enterprises and the government is simulated, with other parameters held constant. As shown in Figure 8, when the supplier's R&D cost is low ($Cr/\alpha = 0.3$), the probabilities of the government subsidizing (x), the supplier investing in R&D for NZEB technologies (y), and the construction enterprise procuring the technology (z) rapidly converge to the stable Evolutionary Stable Strategy (ESS) (1, 1, 1) in the short term. This indicates that a low R&D cost leads to a higher likelihood of consensus among suppliers regarding strategy choice, enabling the system to attain stability as soon as possible.

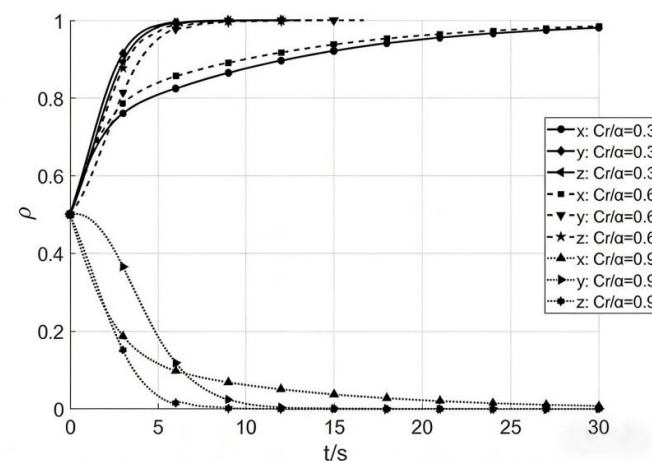


Figure 8. Evolutionary results of changes in the supplier's R&D cost Cr/α .

Conversely, the higher the supplier's R&D cost (Cr/α), the slower the evolution within the system becomes. First, even the probability of government subsidy (x) exhibits a downward trend, although it eventually converges to 1. Overall, the system's efficiency and stability decline significantly. This pattern essentially signals a constraint-adjustment mechanism in the suppliers' decision-making under the influence of R&D costs. Under

low-cost conditions, suppliers are much more likely to reach a consensus on cooperation and innovation. Conversely, under high-cost conditions, suppliers are initially more likely to make conservative choices due to risk aversion. Only over time do they become more willing to adopt the target strategy, thereby significantly lowering overall efficiency and stability.

5.8. Evolutionary Stable States of Strategies

5.8.1. Market-Driven ESS (0, 1, 1): Parameter-Threshold Dependent Stability

Based on the preceding stability analysis, the equilibrium point—representing the state of ‘No Government Subsidy, Supplier R&D, and Enterprise Procurement’—is identified as a stable node contingent on specific market parameters. Mathematically, this state constitutes an ESS only when the market premium for NZEB technologies (P_m) exceeds the incremental cost for construction enterprises (C_b), and the technology maturity coefficient (α) is sufficiently high to lower the effective R&D cost (Cr/α) for suppliers. Under these conditions, the eigenvalues of the Jacobian matrix are strictly negative, ensuring local asymptotic stability. Figure 9 visually confirms this theoretical derivation through numerical simulation.

(0,1,1) - No Government Subsidy, Supplier R&D, Construction Enterprise Procurement (Market-driven ESS)

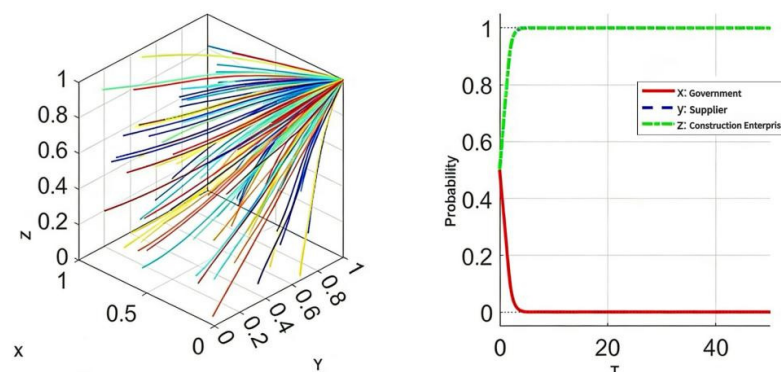


Figure 9. Three-dimensional evolutionary path and evolutionary stable state at equilibrium point (0, 1, 1).

Under these conditions, the payoff for cooperation exceeds that for defection, even without policy intervention. Suppliers voluntarily invest in R&D for NZEB technologies, and construction enterprises actively procure the technology, forming a self-sustaining ‘production–procurement’ feedback loop. This confirms that market mechanisms alone can drive the diffusion of NZEB technologies, but only when technological and economic parameters surpass the critical stability threshold.

5.8.2. Policy-Driven ESS (1, 1, 1): The Compensatory Role of Subsidies

When market mechanisms alone are insufficient (i.e., $P_m < C_b$ or high Cr/α), the system defaults to non-cooperation. In this scenario, the equilibrium (1, 1, 1) is stabilized exclusively through policy intervention. Stability analysis demonstrates that subsidies (S) serve as a compensatory variable; mathematically, a non-zero S alters the eigenvalues’ signs, thereby stabilizing (1, 1, 1). As shown in Figure 10, even a low initial willingness ($x = 0.2$) enables the system to converge to this tripartite cooperation, with higher S expediting the convergence process. This confirms that policy effectively offsets market deficits and accelerates technology diffusion.

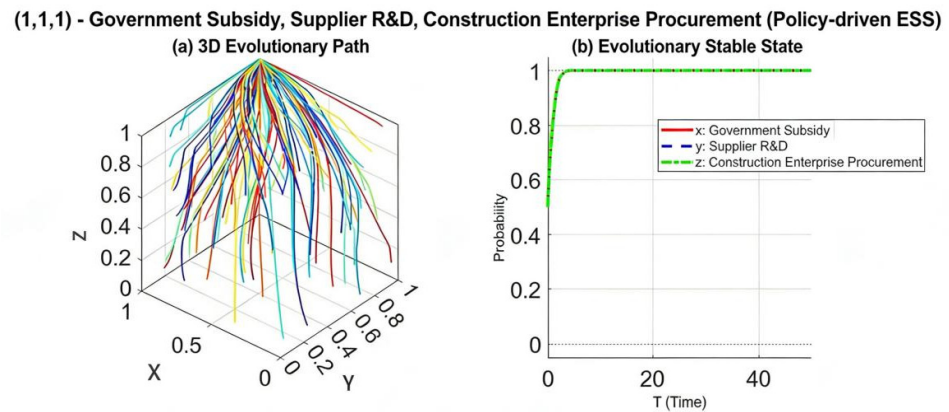


Figure 10. Three-dimensional evolutionary path and evolutionary stable state at equilibrium point (1, 1, 1).

5.8.3. Characteristics of Unstable Equilibrium Positions

As shown in Figures 11 and 12, the partial-cooperation equilibrium points (0, 0, 1) and (0, 1, 0) are identified as unstable saddle points marked by positive eigenvalues (e.g., $Pm > 0$ or $Cr/\alpha > 0$). This mathematical instability reflects a fundamental contradiction in cost–benefit logic: strategy combinations such as ‘suppliers not investing while enterprises adopt’ or ‘suppliers investing while enterprises do not adopt’ are structurally untenable in the long term.

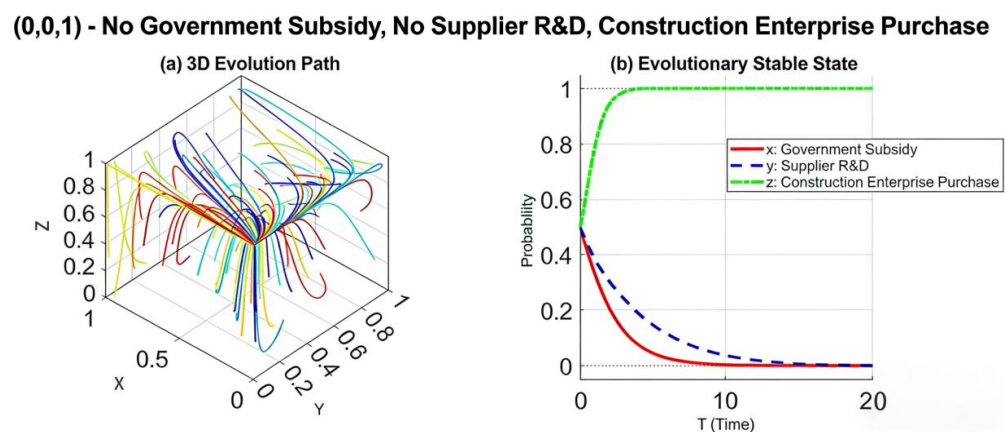


Figure 11. Three-dimensional evolutionary path and evolutionary stable state at equilibrium point (0, 0, 1).

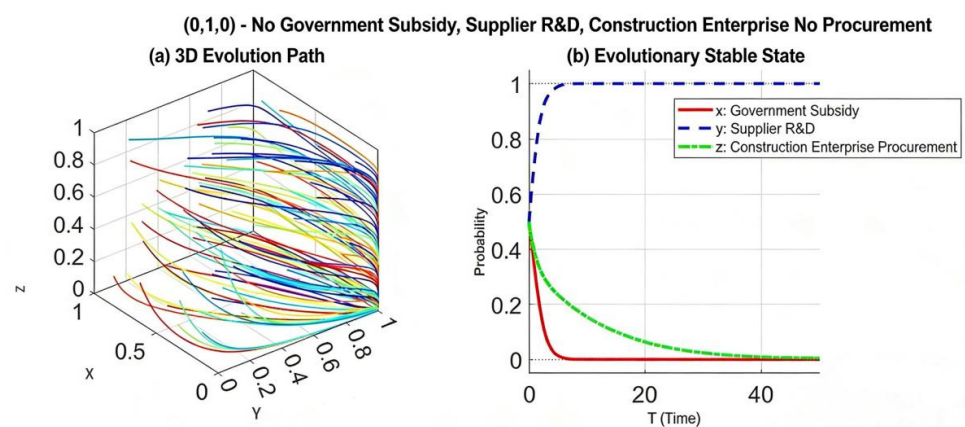


Figure 12. Three-dimensional evolutionary path and evolutionary stable state at equilibrium point (0, 1, 0).

Furthermore, as illustrated in Figure 13, the ‘all-defect’ state (0, 0, 0) functions as a risk-dominant equilibrium only when both market incentives and policy support are

insufficient (i.e., $S < Cr/\alpha$ and $Pm < Cb$). However, once the parameters satisfy the threshold conditions for either market- or policy-driven mechanisms, the system immediately departs from this state, confirming that $(0, 0, 0)$ is not a robust attractor under effective intervention.

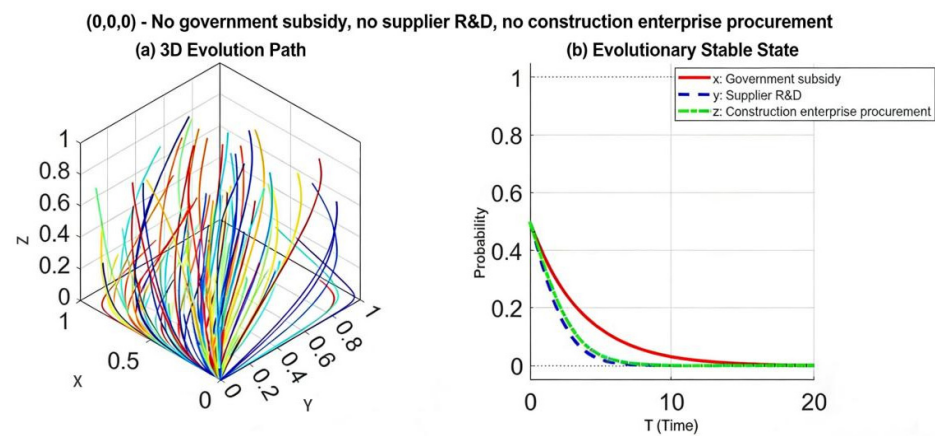


Figure 13. Three-dimensional evolutionary path and evolutionary stable state at equilibrium point $(0, 0, 0)$.

6. Conclusions and Recommendations

6.1. Research Conclusions

Government intervention directly stimulates production by restructuring the stakeholders' payoff matrix through two distinct mechanisms: a subsidy (S) that reduces the effective R&D cost for suppliers (reducing Cr to $Cr - S$), and penalty measures (Fs, Fb) that impose additional costs on passive strategies (non-R&D and non-procurement). When the initial propensity of construction enterprises to procure is low, the system is driven toward cooperation as the combined pressure of incentives and penalties shifts the dominant strategy. This confirms that the government possesses the capacity to fundamentally restructure the cost–benefit landscape, effectively compelling the system to escape the non-cooperative trap through regulatory instruments.

The technology procurement decisions of construction enterprises are highly dependent on the R&D willingness of suppliers (y), demonstrating a significant theoretical linkage between the two. An increase in suppliers' R&D willingness can effectively accelerate the convergence process of enterprises' procurement probability (z), indicating a positive transmission effect from the supply side to the demand side. When suppliers commit to the R&D strategy, the technology supply risk faced by enterprises decreases significantly, rendering enterprises more inclined to implement procurement and thus establishing a stable transmission mechanism where 'R&D supports procurement'. In contrast, when suppliers do not conduct R&D, enterprises lack access to available technology supply; consequently, even with a high initial procurement willingness, their procurement probability declines rapidly. This result theoretically confirms the strict dependence of the demand side on supply-side support.

An increase in enterprises' procurement willingness (z) exerts a significant theoretical pull effect on government subsidy incentives and supplier R&D behavior. A higher willingness of enterprises to procure contributes to increasing the environmental benefits (Re) obtained by the government, thereby improving the cost–benefit structure of government subsidies. Simultaneously, stronger procurement willingness expands the market revenue space for suppliers and furnishes positive motivation for their R&D investment. The government's subsidy strategy evolves toward a stable state across different initial procurement willingness levels. Although the convergence speed of the government's strategy is relatively moderate when the initial procurement willingness is high, the overall

system still exhibits the theoretical characteristic of evolving toward a synergistic state. These results theoretically elucidate the pull effect of enterprise demand on government policy incentives and supply-side decision-making.

6.2. Research Recommendations

(1) The government should establish a targeted policy framework to enhance guidance and constraints.

Based on the theoretical analysis, we recommend that the government adopt a tiered subsidy mechanism: provide stronger R&D subsidies for suppliers with relatively low technological maturity and offer appropriate cost compensation for construction enterprises that procure NZEB technologies at scale, with subsidy intensity optimized gradually as technologies mature. Meanwhile, penalty mechanisms should impose moderate constraints on suppliers that fail to conduct R&D for NZEB technologies and enterprises that do not implement procurement, thereby stabilizing the coordination between supply and demand. Furthermore, the government may refine the carbon pricing mechanism by integrating building carbon emission reductions into the carbon trading system to enhance the market competitiveness of NZEB technologies; offer targeted tax incentives for users of NZEB technologies to stimulate end-user demand and foster the development of a closed-loop market mechanism.

(2) Suppliers should prioritize technological advancement and production capacity to strengthen the supply base.

Based on the theoretical analysis, we recommend that suppliers strengthen cooperation with universities and research institutions to overcome key technical bottlenecks in NZEB technologies, continuously improve technological maturity, and reduce R&D costs. They should establish production bases in pilot regions, stabilize technology supply and market prices through medium- and long-term supply agreements, optimize cost structures via large-scale production, and promote energy-saving and cost-reducing measures such as waste recycling, thereby comprehensively enhancing market competitiveness and laying a solid supply foundation for the large-scale promotion of NZEB technologies.

(3) Construction enterprises are encouraged to optimize procurement strategies and cost management to activate demand-driven processes.

Based on the theoretical analysis, we recommend that enterprises formulate reasonable procurement plans for NZEB technologies based on project-specific realities, achieving scale effects and stabilizing procurement costs by signing long-term cooperation agreements with suppliers. Enterprises should establish internal technical management departments to ensure the implementation of NZEB technologies and capitalize on the advantages of long-term energy-saving benefits. Meanwhile, enterprises should conduct whole-life cycle cost assessments to rigorously evaluate the economic efficiency and feasibility of procurement decisions, actively utilizing green bonds, special credit, and other financial instruments to alleviate financial pressure. Enterprises are advised to proactively participate in government pilot programs, accumulate practical experience, and mitigate risks and trial costs in technology application.

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References

- Hu, D.; Bao, Z.; Wang, J. Comparison of Conceptual Connotations and Main Indicators between Green Buildings and Nearly Zero-Energy Buildings. *Sichuan Shuini* **2024**, *45*, 114–116, 200.
- Xu, W.; Zhang, T.; Kang, Y.; Xian, D.; Liu, R.; Wang, D.; Yu, Z.; Zhang, S. Exploration of Carbon Reduction Pathways for Nearly Zero-Energy Buildings in Cold Climates. *J. Build. Sci.* **2023**, *39*, 1–8.
- Nam, K.; Ahn, H.W.; Lee, S.G.; Kim, J.; Jeong, S.-G. Net Zero Proximity Index and Techno-Economic Analysis of BIPV for Zero Energy and Zero Emission Buildings. *J. Build. Eng.* **2025**, *103*, 112188. [\[CrossRef\]](#)
- Eksi, M.; Akarsu, R.T.; Ozcan, M. Net-Zero Energy Building Transformation: Techno-Economic and Environmental Evaluation in the Mediterranean Region. *Environ. Dev. Sustain.* **2025**. [\[CrossRef\]](#)
- You, R.; Jiang, Y.; Gao, Y.; Sun, D.; Zhang, R.; Zhou, L.; Liu, L.; Li, Y.; Guo, Y.; Fu, Q.; et al. Research on the Application of Nearly Zero-Energy Building Technology in Large Office Buildings in Hot Summer and Warm Winter Zones: A Case Study of China Overseas Building. *Jianzhu Kexue/J. Build. Sci.* **2024**, *40*, 83–91, 270.
- Noh, Y.; Jafarinejad, S.; Anand, P. A Review on Harnessing Renewable Energy Synergies for Achieving Urban Net-Zero Energy Buildings: Technologies, Performance Evaluation, Policies, Challenges, and Future Direction. *Sustainability* **2024**, *16*, 3444. [\[CrossRef\]](#)
- Chen, P.; Sun, C. Conceptual Evolution, Overall Strategy, and Technical Framework of Nearly Zero-Energy Buildings. *Keji Daobao/J. Sci. Technol. Rev.* **2021**, *39*, 108–116.
- Feng, G.; Chen, F.; Chang, S. Multi-Objective Optimization Study on the Envelope of Nearly Zero-Energy Buildings. *J. Shenyang Jianzhu Daxue Xuebao (Ziran Kexue Ban)/J. Shenyang Archit. Civ. Eng. Inst. (Nat. Sci.)* **2023**, *39*, 699–706.
- Kandilli, C.; Gür, M.; Yilmaz, H.; Öztö, H.F. An Experimentally Validated Numerical Model for the Parametrical Evaluation of a Full Scale Innovative Trombe Wall of a Nearly Zero Energy Building Based on Composite Natural Zeolite Plates. *Energy* **2025**, *340*, 139316. [\[CrossRef\]](#)
- Gür, M.; Öztö, H.F.; Yamaç, H.İ.; Gürgeç, E.; Selimefendigil, F. An Experimental Study on Thermal Effects in Building Integrated Semi Transparent Double Skin Façades for a Nearly Zero Energy Building. *Appl. Therm. Eng.* **2026**, *290*, 129995. [\[CrossRef\]](#)
- Xu, W. Research and Practice of Nearly Zero-Energy Buildings in China. *Keji Daobao/J. Sci. Technol. Rev.* **2017**, *35*, 38–43.
- Xu, W.; Yang, X.; Zhang, S. Key Issues and Solutions for the Development of Nearly Zero-Energy Buildings in China. *Jianzhu Kexue/J. Build. Sci.* **2018**, *34*, 165–173. [\[CrossRef\]](#)
- Zou, F.; Zhu, N.; Guo, E.; Du, T. Technical Practice of Nearly Zero-Energy Buildings in Eco-Cities under the “Dual Carbon” Background: A Case Study of Sino-Singapore Tianjin Eco-City. *Lüse Jianzhu/Green Build.* **2023**, *15*, 13–18.
- Shen, Z. Exploration on Energy Efficiency of Nearly Zero-Energy Buildings under the “Dual Carbon” Goal. *Xinxing Jianzhu Cailiao/New Build. Mater.* **2022**, *49*, 14–18.
- Omar, O. Near Zero-Energy Buildings in Lebanon: The Use of Emerging Technologies and Passive Architecture. *Sustainability* **2020**, *12*, 2267. [\[CrossRef\]](#)
- Zhao, Z.; Yuan, Y.; Li, Z.; Liu, H. Brief Introduction to the Development of Nearly Zero-Energy Buildings. *Lüse Jianzhu/Green Build.* **2024**, *16*, 7–9, 24.
- Wang, Y.; Hu, B.; Meng, X.; Xiao, R. A Comprehensive Review on Technologies for Achieving Zero-Energy Buildings. *Sustainability* **2024**, *16*, 10941. [\[CrossRef\]](#)
- Pierozan, E.; Piccinini Scolaro, T.; Watzko, E.S.; Ghisi, E. Technical and Economic Feasibility of Multi-Family Social Housing and Nearly Zero-Energy Buildings in Southern Brazil. *Sustainability* **2024**, *16*, 2608. [\[CrossRef\]](#)
- Li, J.; Wang, Z.; Dong, Y.; Zhou, J. Evolutionary Analysis of Stakeholder Decisions in Power Battery Recycling with Learning Effects and Carbon Trading. *Environ. Dev. Sustain.* **2025**. [\[CrossRef\]](#)
- Lv, W.; Li, J. How Carbon Taxes and Subsidies Affect the Implementation of Low-Carbon Housing? An Evolutionary Game Theory Analysis. *Front. Environ. Sci.* **2025**, *13*, 1679245. [\[CrossRef\]](#)
- Zhang, Y.; Lu, Z.; Zhang, W. Policy Synergy for Conflicting Interests in Low-Carbon Innovation: An Evolutionary Game Analysis of Dynamic Incentives and Risk-Sharing in China’s Urban Renewal. *Sustainability* **2025**, *17*, 9924. [\[CrossRef\]](#)
- Zhang, Q.; Zhao, D.; Wang, J. Analysis of Enterprise Low-Carbon Technology Innovation via a Tripartite Evolutionary Game under Dual Supervision. *Front. Environ. Sci.* **2025**, *13*, 1623520. [\[CrossRef\]](#)
- Lu, Q.; Yu, S.; Huang, G. Dynamic Evolutionary Game Simulation Analysis of Government Carbon Regulation and Heavy Pollution Enterprise Carbon Reduction Strategies. *Chongqing Ligong Daxue Xuebao (Ziran Kexue Ban)/J. Chongqing Univ. Technol. (Nat. Sci.)* **2022**, *36*, 255–267.

24. Liang, X.; Fu, Y. Research on the Evolutionary Game of Green Building Supply Side under Government Dynamic Reward-Punishment Mechanisms. *Zhongguo Guanli Kexue/Chin. J. Manag. Sci.* **2021**, *29*, 184–194. [[CrossRef](#)]
25. Gao, Y.; Liu, J.; Zhang, J.; Xie, H. Modeling the Evolutionary Mechanism of Multi-Stakeholder Decision-Making in the Green Renovation of Existing Residential Buildings in China. *Buildings* **2025**, *15*, 2758. [[CrossRef](#)]
26. Li, J.; Xu, N.; Liu, Q.; Zhao, H. How to Promote the Application of Green Construction Technologies in the Chengdu-Chongqing Economic Circle: A Tripartite Evolutionary Game Analysis. *Buildings* **2025**, *16*, 62. [[CrossRef](#)]
27. Ma, L.; Du, X.; Gao, F.; Yang, Y.; Gao, R. Study on Low-Carbon Planning and Design Strategies for University Campus Built Environment. *Buildings* **2026**, *16*, 1274. [[CrossRef](#)]
28. Zhao, Y.; Ma, Y.; Zhong, F. Sustaining Green Building Incentives: A Tripartite Evolutionary Game Analysis and the Synergistic “Technology–Reputation–Policy” Pathway. *Buildings* **2025**, *15*, 1537. [[CrossRef](#)]
29. Ning, X.; Ye, X.; Wang, W. Research on the Evolutionary Path of High-Quality Innovation and Development of Green Residential Buildings under the “Dual Carbon” Background. *Xitong Gongcheng Lilun Yu Shijian/Syst. Eng. Theory Pract.* **2023**, *43*, 2653–2668.
30. Jiang, J.; Yang, C.; Chen, L.; Ma, Z.; Lin, L.; Fu, X. Tripartite Evolutionary Game Analysis of Carbon Emission Reduction in Shipping Enterprises under the “Dual Carbon” Goal. *Jiaotong Xinxi Yu Anquan/J. Transp. Inf. Saf.* **2023**, *41*, 152–160.
31. Zhang, X.; Duan, X.; Zhou, X.; Pang, Z.; Duan, H.; Teng, Y.; Xu, H. Study on the Behavioral Decision of Multiple Subjects of Agricultural Green Production under the Double Carbon Target in China. *Front. Public Health* **2025**, *13*, 1575121. [[CrossRef](#)]
32. Xu, H.; Ye, C.; Li, F. Evolutionary Game Analysis of Carbon Emission Reduction in Supply Chain Enterprises under Government Regulation. *Ruan Kexue/Soft Sci.* **2025**, *39*, 107–114. [[CrossRef](#)]
33. Shao, S.; Wang, Q.; Liu, Y. Research on Green Transformation of Small and Medium-Sized Manufacturing Enterprises under Government Dynamic Reward-Punishment Mechanisms. *Zhongguo Guanli Kexue/Chin. J. Manag. Sci.* **2025**. [[CrossRef](#)]

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