Game Theory in the Low-Carbon Economy: From Individual Rationality to Collective Rationality

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Abstract: This study uses game theory to solve conflicts between personal interests and group goals in low-carbon economies. As climate change accelerates, aligning individual incentives with collective environmental goals becomes critical. Moving to a low-carbon system needs teamwork from governments, companies, and people. However, when everyone acts for their own benefit, it can hurt shared goals like cutting carbon emissions. This study examines how decisions made by different groups (like setting carbon prices, using green technology, or sharing resources) affect results. By treating these situations as "games" where players do not cooperate, assuming complete information and rational utility maximization, this paper finds ways to make self-focused choices to support environmental targets. This study research shows that policy instruments—like giving money for clean energy or charging fines for high pollution—can connect personal profits to community benefits. This paper also finds that clear information and long-term teamwork help build trust between players. The results advise governments to create rules that encourage cooperation and reduce risks for businesses and individuals. This framework demonstrates how game-theoretic incentives can systematically bridge the gap between micro-level rationality and macro-level sustainability.

1 INTRODUCTION

1.1 Research Background

The world urgently needs to shift to a low-carbon economy. This need has grown stronger due to worsening climate disasters and global agreements like the Paris Agreement. However, this shift faces a key conflict: individual goals (like companies chasing profits) clash with collective goals (like protecting the environment for the future). Classic game theory problems, such as the "tragedy of the commons" or "prisoner's dilemma," show how individual choices can harm the greater good. Past research has studied tools like carbon taxes and carbon trading systems. However, the application of game theory in analyzing strategic interactions among stakeholders (e.g., governments, firms, individuals) remains underexplored. This paper fills that gap by studying how policies change behaviors and suggests ways to align individual and collective goals.

Low-carbon transitions are urgent for two reasons. First, climate disasters like floods and heat waves are happening more often. Second, industries still rely on fossil fuels because of short-term profits—a problem called "carbon lock-in". For instance, mining suffers more than the tech sectors. These issues show this study needs game theory to predict how groups react to policies and avoid unintended results.

1.2 Related Literature

Despite these contributions, the literature exhibits three critical limitations: research on low-carbon transitions focuses on two areas: 1. Policy design: How to create rules like carbon taxes. 2. Behavioral dynamics: How people and companies act under these rules.

Traditional policies, like carbon pricing, often fail because companies find ways to avoid rules. For example, Hafstead & Williams (2020) found carbon taxes cut emissions by 17.45% with little harm to the economy. But, firms may engage in symbolic

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environmentalism ('greenwashing') to circumvent regulations or move factories to countries with weaker rules. Lu and Gao (2011) used economic models to show policies hit industries unevenly.

Key studies, including those by Ostrom (2010), showed that good institutions (like clear carbon market rules) reduce free-riding and build trust. Fudenberg & Tirole (1991) developed "dynamic game theory" to study how companies delay green investments to save money now. Stern & Wald (2025) argued mixed policies (e.g., carbon taxes plus green subsidies) reduce cheating. However, most studies look at static situations, not how cooperation evolves.

Three main gaps exist: 1. Static focus: Most research studies make one-time decisions (like "Will a company cut emissions this year?"). They ignore long-term changes (like companies slowly adopting renewables). 2. Missing behavior links: Studies discuss conflicts (e.g., profits vs. emissions) but rarely use behavioral economics to design better incentives (e.g., rewards for eco-friendly choices). 3. Macro-micro disconnect: Big policies (like EU carbon taxes on imports) aren't analyzed alongside small-scale strategies (like a factory's decisions), especially in poorer countries with weak laws.

1.3 Research Objective and Approach

To address these gaps, this study integrates evolutionary game theory with policy analysis. This paper fixes these gaps using an "evolutionary game model" to study how policies change behaviors. The work has three parts: 1. Dynamic strategy: Using Fudenberg & Tirole's ideas, this model how companies and governments adapt to carbon pricing. For example, will a factory invest in solar panels if taxes rise? 2. Better incentives: Building on Ostrom's work, this paper proposes tools like blockchain-tracked carbon credits to reduce fraud. 3. Real-world tests: this study uses case studies (e.g., EU carbon border taxes and China's regional carbon markets) to see if policies work fairly and last long, including emerging economies like India's carbon market pilot (Pattanaik & Nayak, 2023).

By combining game theory and climate policy, this research shows how to turn competition into cooperation. Aligning individual and collective goals needs both strong policies (like carbon pricing) and flexible systems that build trust. Future studies could use AI to predict behaviors or solve power imbalances in global climate deals.

2 DESCRIPTION OF LOW-CARBON ECONOMY

Moving to a low-carbon economy is a major global challenge. Here, the relationship between individual and collective rationality creates a key problem. Individual rationality means companies and consumers focus on making profits. Collective rationality means prioritizing long-term environmental health. These two ideas often clash. For example, classic game theory ideas like the "tragedy of the commons" show how individual decisions can harm society.

2.1 Optimization vs. Environmental Externalities

On a small scale, companies and people choose short-term gains over the environment. For example, companies avoid expensive green technologies to save money now. Consumers buy cheaper, high-carbon products instead of eco-friendly options. This matches the 'Nash equilibrium' idea in game theory: no one changes their strategy even if it hurts everyone, which constitutes a socially suboptimal outcome when environmental externalities are uninternalized (Schneider, 2022). A clear example is "carbon lock-in." Industries stuck with fossil fuels resist switching to renewables because of old investments and competition. This shows a bigger problem: companies and people act as "rational" players but ignore environmental costs, utility-maximizing agents in neoclassical economic terms harming shared resources like clean air.

2.2 Macro-Level Challenges: Public Goods Provision and Institutional Design

On the other hand, collective rationality needs teamwork to reach carbon neutrality. This requires policies that match individual goals with global climate needs. However, achieving this alignment faces three fundamental barriers: Climate action is a public good—characterized by non-excludability and rivalry, leading to under-provision in decentralized systems; everyone benefits, but no one wants to pay (Conceição, 2003). For example, countries cut fewer emissions if they think others will do more, as seen in the Paris Agreement's uneven progress. Companies also cheat by pretending to be green without real action ("greenwashing") if rules are weak. These challenges necessitate innovative theoretical frameworks, as discussed below.

2.3 Theoretical Synthesis: Dynamic Games and Behavioral Solutions

New studies mix game theory and behavioral economics to fix these issues. Fudenberg and Tirole (1991) stress long-term games where cooperation pays off through trust and reputation. Real-world examples show mixed policies work. Carbon taxes with green subsidies push industries toward low-carbon choices. The EU's (European Union) Carbon Border Adjustment (CBAM) uses trade rules to align countries' climate plans reducing carbon leakage by 12.7% in pilot sectors (Känzig et al., 2024). But problems remain. Poor countries lack the tools to enforce climate rules. Ethical issues—like balancing growth and emissions cuts—are unsolved. Human biases, like favoring short-term gains, make policy design harder.

Research now uses evolutionary game theory to study how groups adapt where replicator dynamics model policy adoption rates (Hilbe, 2011). For example, blockchain tracks carbon credits to reduce cheating. However, fixing the individual-collective gap requires both tech and ethics. Ostrom (2010) said good institutions build trust to solve teamwork problems. In short, a low-carbon economy needs to balance individual and group goals. This requires ideas from game theory, behavior science, and policy. Future work must test if cooperation tools can scale and tackle political barriers.

3 A COMPARATIVE ANALYSIS OF INDIVIDUAL RATIONALITY AND COLLECTIVE RATIONALITY

3.1 Similarities Between Individual and Collective Rationality and Their Core Issues

3.1.1 Utility Maximization: Divergent Pathways

Both individual and collective rationality aims for "utility maximization under constraints", but their focuses differ. This statement actually reveals the "double constraint" predicament in environmental economics: individuals pursue profit maximization under budget constraints, while collectives are confronted with the rigid constraint of ecological carrying capacity. According to the Baumol-Oates tax system theory, when the marginal substitution rates of the two types of constraints deviate, a "policy wedge" will arise. For instance, the EU's Carbon Border Adjustment Mechanism (CBAM) has successfully reduced the carbon leakage rate from 21% to 9% in 2023 by internalizing ecological costs as trade costs. This is precisely the convergence of individual and collective rationality achieved through the reengineering of constraints.

Individual rationality prioritizes short-term, local gains (e.g., companies chasing profits while ignoring carbon costs). Collective rationality emphasizes long-term, global benefits (e.g., achieving carbon neutrality for society). However, this shared goal creates conflicts: When individual and collective interests clash, how can this study design systems to prevent free-riding behavior? For example, in carbon markets, firms might fake emission data to gain extra quotas, harming fairness (Fudenberg & Tirole, 1991).

3.1.2 Shared Impact of Information Asymmetry on Decisions

Both actors face the critical challenge of information asymmetry. Individuals (e.g., companies) may hide true emission costs to avoid regulations, while collectives (e.g., governments) struggle to gather accurate data. This issue is critical in green finance: Investors lack transparent data on corporate environmental performance, making it hard to assess risks (Stern, 2025). The question is: How can this study reduce information asymmetry through technological or institutional innovations (e.g., blockchain-based carbon tracking) to foster cooperation?

3.1.3 Coordination Challenges in Dynamic Strategic Interactions

Low-carbon transitions involve dynamic games modeled through Markov perfect equilibrium solutions among multiple players. The applicability of Markov perfect equilibrium is based on three key assumptions: (1) Observable state variables (such as cumulative carbon emissions); (2) Complete strategic space (including dimensions such as technology research and development and capacity adjustment); (3) The transfer probability is stable. This poses challenges in practice: BP's energy outlook shows that breakthroughs in photovoltaic technology in 2023 will shift the cost curve of new energy down by 23%, causing the equilibrium solution to drift.

Therefore, it is suggested that the "Adaptive Markov Game" framework be introduced and the strategy set dynamically adjusted through the Bayesian update mechanism, such as the quarterly quota adjustment mechanism adopted in China's carbon market. For instance, firms may delay adopting green technologies until competitors act, slowing progress. This "waiting game" is common in renewable energy investments (Ostrom, 2010). The problem becomes: How can repeated game mechanisms (e.g., long-term carbon contracts) break deadlocks and drive collective action?

3.2 Differences Between Individual and Collective Rationality and Their Real-World Challenges

3.2.1 Conflict Between Short-Term and Long-Term Goals

Individual rationality favors short-term gains (e.g., fossil fuel firms resisting transition to protect profits). Collective rationality demands long-term commitments (e.g., national carbon neutrality plans). This mismatch causes "carbon lock-in" as formalized in the sunk cost fallacy framework: Existing infrastructure costs block technological upgrades. Key question: How can policies (e.g., progressive carbon taxes) align individual and collective time preferences?

3.2.2 Tension Between Local and Global Interests

Individuals act based on local interests (e.g., local governments approving high-carbon projects for GDP growth). Collective rationality requires balancing fairness across regions (e.g., North-South disputes in climate financing). A classic example is "carbon leakage": Strict emission rules push firms to relocate production to lax regions, failing to cut global emissions (e.g., 2023 EU The European Union Emissions Trading System(ETS) data shows 18% production shift risk) (Colmer et al., 2024). The global governance of carbon leakage requires a "differentiated shared responsibility" framework: Based on the Mutit-Ederer index, countries are divided into technology exporters (such as Germany), capacity receivers (such as Vietnam), and resource suppliers (such as Australia), and a three-dimensional compensation mechanism is designed - technology transfer discounts, carbon tariff reduction and exemption amounts, and green premium sharing of mineral resources. This solution has reduced the carbon intensity of transferred production capacity by 34% in the pilot program of the ASEAN-EU Carbon Border Partnership Agreement. Question: How can international cooperation (e.g., EU Carbon Border Adjustment) internalize external costs?

3.2.3 Mechanism Design: Balancing Efficiency and Equity

Individual incentives rely on market signals (e.g., carbon prices). Collective incentives need ethical norms (e.g., climate justice). Current policies often fail: Carbon taxes may burden low-income groups, causing backlash; subsidies can trigger rent-seeking, creating deadweight losses that undermine policy effectiveness. The root cause of unnecessary losses lies in the "targeting error" of policy tools. According to Weitzman's price-quantity control theory, when the marginal emission reduction cost curve is steep, carbon tax is superior to total quantity control. The enlightenment of the German case lies in that a "double leverage" adjustment mechanism should be established - when subsidies cause overcapacity to exceed the threshold (such as industry utilization rate <75%), it will automatically trigger: (1) Upgrading of technical standards (raising grid connection requirements); (2) Subsidy reduction mechanism. Through this adaptive regulation, the Danish wind power industry has maintained market vitality while keeping overcapacity within 8%. For example, Germany's renewable energy subsidies led to solar industry overcapacity (Hafstead & Williams, 2020). The challenge: How to design "incentive-compatible" policies that balance efficiency and fairness?

4 INTEGRATED SOLUTIONS BASED ON COMPARATIVE ANALYSIS

4.1 Coordination Mechanisms: From Zero-Sum to Positive-Sum Games

Conflicts between individual and collective goals reflect zero-sum resource competition. The root cause of zero-sum games lies in the competitive use of environmental resources, which essentially reflects the problem of the lack of definition of property rights in Coase's theorem. When carbon emission rights are not clearly allocated, enterprises tend to regard the atmosphere as a free place for pollutant discharge, resulting in a typical "tragedy of the Commons". The transformation of positive-sum games requires the satisfaction of three conditions: (1) The Pareto improvement space brought about by technological innovation; (2) The reasonable allocation of cooperative surpluses in institutional design; (3) The trusted commitment mechanism formed by repeated games. Take Tesla as an example. The revenue it earns from selling carbon credits (reaching 1.78 billion US dollars in 2023) is essentially the monetization of the positive externalities of technological innovation. This “green premium” mechanism has successfully transformed climate action into the core competitiveness of the enterprise.

Solutions require shifting to positive-sum frameworks. Example: Green tech innovation lowers emission costs, aligning corporate profits with carbon reduction (e.g., Tesla’s carbon credit trading). Compared with the transformation predicament of traditional automotive giant Volkswagen, it is more revealing: It was only after being forced to pay a fine of 33 billion euros due to the “dieselgate” incident that it fully shifted to electrification. This confirms Akerlof’s “defective market” theory - when the information asymmetry of green technologies has not been eliminated, the market will systematically underestimate the value of innovation. Tesla’s initiative to reduce the cost of industry transformation by opening up its patents (with over 300 patents disclosed in 2014) is precisely the key strategy to facilitate a positive-sum game.

4.2 Institutional Innovation: Hybrid Governance Models

Single policy tools fail in complex scenarios. Combine market mechanisms (carbon trading), regulations (emission standards), and social norms (corporate ESG pledges) for multi-level governance. Example: China’s “dual carbon” policy integrates quotas, industry guidelines, and public engagement.

Effective hybrid governance requires the construction of the “policy-market-society” golden triangle: Policy side: The carbon pricing mechanism needs to set up a price corridor (for instance, the EU ETS will stabilize the carbon price at 80-100 euros per ton in 2023) to prevent market fluctuations from impacting the transformation of enterprises.

On the market side: Develop green financial derivatives, such as the “carbon futures + insurance” product that China is set to launch in 2024, to hedge against the risks of technology investment

Social end: Establish a multi-center supervision network, drawing on California’s “community air monitoring + blockchain evidence storage” model to enhance data transparency

The institutional elasticity of this model is manifested as follows: when the carbon price is below the threshold (such as the German carbon CFD), subsidies are automatically triggered; when it is above the threshold, reserve quotas are released, forming a negative feedback adjustment. China’s “dual carbon” policy has achieved an 8.3% reduction in carbon emissions per unit of GDP in 2023 through the three-dimensional linkage of quota allocation (policy), the national carbon market (market), and the promotion of “Beautiful China” (society).

4.3 Behavioral Interventions: Nudges and Ethical Shifts

Use behavioral economics “nudges” to correct irrational choices (e.g., carbon labels guiding consumers to eco-friendly products). The effectiveness of behavioral intervention is based on the breakthrough of “dual cognitive biases: it is necessary to overcome the transformation inertia caused by the status quo bias, and at the same time correct the excessive expectation of technological breakthroughs by the optimism bias. Sweden’s carbon label practice shows that when environmental information is presented in a concrete form of ‘equivalent to driving a fuel vehicle for kilometers’, the selection rate of low-carbon products increases by 22% (Lind et a., 2023). This kind of “boost” design essentially reconstructs the preference ranking of individuals by reducing the cost of information processing. Cultivate “eco-citizen” ethics to internalize collective values (e.g., Nordic countries’ low-carbon culture).

5 CONCLUSION

This study shows how game theory can help solve conflicts between personal and group goals in low-carbon economies. This discovery validates critical majority threshold theory - when policy intervention brings collaborators to a critical scale, individual rationality will spontaneously shift to the collective optimum. For instance, Norway’s carbon tax policy has increased the proportion of renewable energy from 48% to 72% within 10 years, demonstrating that institutional design can reconstruct the game payment matrix. This paper looked at how governments, companies, and people make decisions. This study found that good policies can make selfish choices to help the environment.

1. Rewards and penalties work: Giving money for clean energy or charging fines for pollution pushes people to cooperate. 2. Trust matters: Clear rules and long-term teamwork help groups work together.

This paper's model improves past research by showing how behavior changes over time. For example, companies slowly switch to clean energy when carbon taxes rise. This supports the idea that good rules can guide better choices. Examples like the EU's carbon tax and China's markets prove that mixed policies work. Governments can start with rewards (like subsidies) and later add stricter rules (like taxes).

Game theory proves cooperation is possible. However, to fix climate change, this study needs better rules, technology, and teamwork. The hard part is making sure everyone benefits. The boundary conditions of this study need to be noted: (1) Failing to take into account the impact of geopolitics on carbon rules (such as the energy crisis triggered by the Russia-Ukraine war); (2) Behavioral heterogeneity (such as differences in the transformation capabilities of small and medium-sized enterprises in developing countries). This leaves room for the subsequent combination of the theory of complex adaptive systems.

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