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Review

Evolutionary Game Theory for Sustainable Energy Systems: Strategic Bidding, Carbon Pricing, and Policy Optimization for Clean Energy Development

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ABSTRACT: As the world transitions toward a low-carbon economy, carbon pricing mechanisms, including carbon taxes and emissions trading systems, have emerged as fundamental policy instruments for reducing greenhouse gas emissions, particularly within the electricity sector. This comprehensive review examines the impact of these mechanisms on energy market dynamics through the analytical framework of evolutionary game theory (EGT), modeling strategic interactions among power generation companies, renewable energy firms, and regulatory authorities. Our analysis demonstrates that carbon pricing systematically increases operational costs for fossil fuel-based power plants while simultaneously providing competitive advantages to renewable energy producers, accelerating the adoption of cleaner energy technologies. The study emphasizes the critical role of coordinated policy interventions, including subsidies, penalties, and green certificate systems, in facilitating the adoption of clean technologies and optimizing market transition pathways. These findings underscore the importance of well-designed policy frameworks that align economic incentives across all stakeholders to drive sustainable energy system transformation. Additionally, this research demonstrates how EGT can effectively model the strategic bidding behavior of energy firms, providing valuable insights for optimal decision-making under carbon pricing fluctuations. Through comprehensive case studies and simulation analysis, the paper illustrates how firms can leverage evolutionary strategies to optimize investments in clean technologies, enhance inter-firm cooperation, and stabilize market dynamics. This work further explores future research directions, particularly the integration of machine learning and real-time data analytics with EGT to enhance predictive capabilities and strategic decision-making processes. By establishing connections between EGT and real-world energy market dynamics, this study provides a robust analytical framework for understanding long-term behavioral trends in energy markets. The results contribute significantly to the interdisciplinary literature at the intersection of game theory, energy policy, and sustainability science, offering valuable insights for policymakers, researchers, and industry leaders advancing clean energy transition strategies.

Keywords: Evolutionary game theory; Renewable energy systems; Carbon pricing mechanisms; Strategic bidding optimization; Energy market dynamics; Sustainability policy optimization

1. Introduction

Since the 21st century, the global energy transition has emerged as a prominent trend. The dependence on traditional fossil energy has continuously decreased, while renewable energy sources such as wind and solar energy have witnessed robust development [1]. However, this transition has introduced unprecedented complexity in energy market operations, particularly regarding strategic interactions among diverse market participants under evolving carbon pricing mechanisms. The "World Energy Outlook" report by the International Energy Agency (IEA) shows that the proportion of fossil energy in global energy consumption has been declining year by year, whereas the share of renewable energy has been rising rapidly [2]. Despite extensive research in energy economics and game theory, the dynamic strategic behaviors of energy market participants under carbon constraints remain insufficiently understood, particularly regarding the long-term evolutionary patterns that emerge from repeated interactions among heterogeneous

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agents. Take the annual newly installed capacity of global renewable energy as an example. It has leaped from 666 gigawatts in 2024 to nearly 935 gigawatts in 2030 [3]. China has stood out in this process. As shown in Figure 1, its renewable energy capacity is expected to increase by more than 2500 gigawatts from 2017 to 2030, far exceeding that of the European Union (about 1500 gigawatts) and the United States (about 1000 gigawatts).

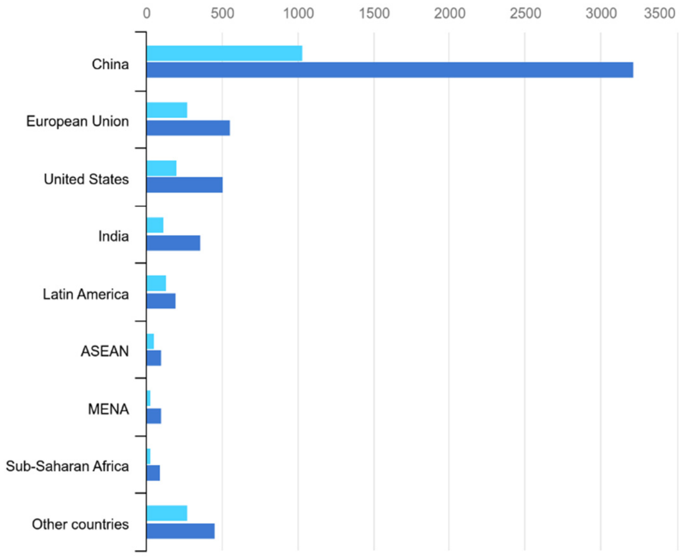


Figure 1. Regional analysis of renewable energy capacity expansion trajectories from 2017 to 2030, demonstrating China's leadership in global clean energy development with projected capacity additions exceeding 2500 GW, compared to the European Union (1500 GW) and the United States (1000 GW). Data source: International Energy Agency World Energy Outlook 2024.

Multiple factors, including technological progress, cost reduction, and policy support from various countries drive the global energy transition. The signing of the Paris Agreement in 2015 demonstrated the firm determination of the international community to tackle climate change. Countries have successively set carbon neutrality goals. For instance, the European Union's "Green New Deal" commits to achieving carbon neutrality by 2050, China plans to reach this goal by 2060, and the United States has also announced the achievement of net-zero emissions by 2050. To attain these goals, it is imperative to reduce the use of fossil energy and accelerate the development and utilization of renewable energy. Meanwhile, international climate agreements have promoted the widespread application of carbon pricing mechanisms, such as carbon trading and carbon taxes, which have profoundly transformed the cost structure and market competition landscape of the energy industry [4]. Renewable energy sources, especially wind energy, solar energy, and biomass energy, are of great significance for reducing greenhouse gas emissions and addressing climate change. With the continuous decline in the costs of wind and solar energy, they have become the core alternatives to fossil fuels. By 2050, renewable energy is estimated to meet two-thirds of the global energy demand and create enormous opportunities for economic growth and employment [5]. To realize this objective, it is necessary to accelerate the deployment of technologies and innovate policies, especially to improve the efficiency of power transmission, enhance the flexibility of the energy system, and boost energy efficiency. Therefore, renewable energy is not only the key to reducing carbon emissions but also an important driving force for global sustainable development.

However, the development of renewable energy does not proceed without obstacles. Its high investment cost and obvious intermittency of power supply pose challenges to the stable operation of the power system. For example, the issue of power stability has become more prominent, and the demand for energy storage technology has significantly increased [6].

Against this backdrop, the reform of the electricity market (EM) has become a crucial measure, covering aspects such as the restructuring of the market structure, the introduction of the wholesale market, and the transformation of regulatory approaches. For example, the electricity spot market and ancillary service market in Europe provide an important platform for the consumption of renewable energy, and the application of distributed energy trading and blockchain technology has brought new opportunities for the intelligent and decentralized development of the EM.

At the same time, the carbon pricing mechanism has changed the cost structure of power generation enterprises. Taking the European Union Emissions Trading System (EU ETS) as an example, the rise in carbon prices has significantly increased the cost of power generation from fossil energy, prompting enterprises to adjust their bidding strategies and shift towards clean energy power generation [7]. However, traditional bidding strategies have gradually revealed their limitations in a complex market environment. Static optimization methods are difficult to capture the dynamic changes in the market, and the single-agent decision-making model ignores the interactive competition among multiple agents. Therefore, it is urgent to introduce advanced dynamic game analysis methods. These methods can not only simulate the long-term behavior evolution of market participants but also provide a scientific basis for policy formulation and the optimization of bidding strategies.

Currently, existing research predominantly employs static game-theoretic approaches that fail to capture the dynamic evolutionary nature of energy market transitions under carbon constraints. Second, while carbon pricing mechanisms have been extensively studied in isolation, their integration with strategic bidding behaviors and multi-agent interactions remains superficially addressed. Third, the policy optimization aspects of energy market games, particularly the design of incentive mechanisms that promote sustainable energy transitions, have received inadequate attention in review literature. Fourth, the behavioral economics dimensions of energy market participants, including bounded rationality and learning dynamics, are largely overlooked in existing comprehensive reviews. Finally, the interdisciplinary integration of machine learning and real-time analytics with evolutionary game theory (EGT) approaches represents an entirely unexplored frontier in current review studies. These gaps collectively demonstrate the urgent need for a systematic review that bridges game theory, energy policy, and sustainability science through an evolutionary lens.

Despite the substantial body of research in energy economics and game theory, several critical gaps persist that limit our understanding of sustainable energy transitions. First, the dynamic strategic evolution of energy market participants under carbon pricing mechanisms lacks comprehensive theoretical frameworks that can predict long-term market behaviors and stability conditions. Second, the complex interdependencies between carbon pricing policies, renewable energy subsidies, and strategic bidding behaviors remain poorly understood, particularly regarding their combined effects on market efficiency and environmental outcomes. Third, existing models inadequately address the behavioral heterogeneity of market participants, failing to account for varying adaptation rates, risk preferences, and learning capabilities among different agent types. Fourth, the policy optimization dimension of energy market design has received insufficient attention, particularly regarding the sequential implementation of regulatory interventions and their dynamic effects on market evolution.

This review makes several distinctive contributions that advance the current state of knowledge in energy game theory and sustainability science. First, we provide the most comprehensive synthesis to date of EGT applications in energy systems, establishing a unified theoretical framework that bridges static optimization approaches with dynamic behavioral evolution. Second, we systematically analyze the strategic interactions between carbon pricing mechanisms and energy market bidding behaviors, revealing critical insights for policy optimization that have not been addressed in existing review literature. Third, we introduce novel perspectives on multi-agent cooperation and competition dynamics in carbon-constrained energy markets, providing theoretical foundations for understanding long-term market stability and transition pathways. Fourth, we comprehensively evaluate policy intervention mechanisms through an evolutionary lens, offering evidence-based recommendations for designing effective incentive structures that promote sustainable energy transitions. Fifth, we identify and articulate future research directions integrating machine learning, behavioral economics, and real-time analytics with EGT, establishing a roadmap for next-generation energy market analysis tools.

The remainder of this paper will provide a systematic and comprehensive analysis of EGT applications in sustainable energy systems. Section 2 examines carbon pricing mechanisms and EM bidding dynamics, establishing the foundational understanding of how carbon costs influence strategic behaviors and market clearing processes. This section analyzes both carbon tax and emissions trading systems, comparing their differential impacts on various market participants and their implications for bidding strategy optimization. Section 3 provides an in-depth exploration of EGT and its applications in power markets. It reviews theoretical foundations, methodological approaches, and empirical applications while identifying the unique advantages of evolutionary approaches over traditional static game models.

Section 4 presents the core analytical framework through evolutionary game modeling of bidding strategies under carbon pricing mechanisms, including comprehensive simulation analyses that demonstrate the dynamic evolution of market behaviors under various policy scenarios. This section integrates theoretical modeling with extensive computational experiments to reveal critical insights about market stability, convergence properties, and optimal policy configurations. Section 5 translates theoretical findings into practical policy implications for sustainable energy transition, providing evidence-based recommendations for policymakers regarding carbon pricing optimization, renewable energy support mechanisms, and market design principles.

Section 6 outlines future research directions and methodological advancements, identifying emerging opportunities for integrating machine learning, behavioral economics, and real-time analytics with EGT approaches. Finally, Section

7 synthesizes the key findings and contributions of this review, articulating the broader implications for energy policy, market design, and sustainability science while highlighting the transformative potential of evolutionary approaches for addressing complex energy transition challenges.

Overall, this comprehensive review holds profound significance for advancing theoretical understanding and practical applications in sustainable energy systems. Theoretically, our synthesis establishes EGT as a critical analytical framework for understanding complex energy market dynamics, providing researchers with robust methodological foundations for investigating strategic interactions under carbon constraints. The integration of behavioral economics insights with evolutionary approaches offers unprecedented opportunities for developing more realistic models of energy market participants, moving beyond the limitations of perfect rationality assumptions that have constrained previous research.

From a practical standpoint, our findings provide policymakers and industry stakeholders with evidence-based guidance for designing effective carbon pricing mechanisms, optimizing renewable energy support policies, and managing energy market transitions. The policy implications derived from evolutionary game analysis offer actionable insights for achieving climate objectives while maintaining market efficiency and economic stability. Furthermore, our identification of future research directions establishes a forward-looking research agenda that positions the academic community to address emerging challenges in energy system decarbonization through innovative interdisciplinary approaches. The prospective integration of machine learning and real-time analytics with EGT represents a paradigmatic shift toward intelligent, adaptive energy market management systems that can respond dynamically to technological innovations, policy changes, and environmental uncertainties. Thus, this review serves as a comprehensive state-of-the-art analysis and a catalyst for transformative research that will shape the future of sustainable energy systems.

2. Carbon Pricing Mechanisms and Electricity Market Bidding Dynamics

2.1. Theoretical Foundations of Carbon Pricing Mechanisms

Against the backdrop of the global community's active response to climate change and its all-out efforts to promote carbon emission reduction, the carbon pricing mechanism has emerged as a crucial policy tool grounded in fundamental economic principles that address market failures inherent in environmental externalities. The theoretical foundation of carbon pricing rests upon the seminal work of Arthur Pigou, whose analysis of negative externalities demonstrated that market mechanisms alone cannot achieve socially optimal outcomes when production activities impose costs on third parties without compensation. Carbon emissions represent a quintessential example of such externalities, where the social costs of greenhouse gas emissions significantly exceed the private costs borne by emitting entities, necessitating corrective interventions to internalize these external costs and restore market efficiency [8].

The economic theory underlying carbon pricing mechanisms acknowledges that atmospheric carbon dioxide functions as a global commons, creating what Garrett Hardin conceptualized as a tragedy of the commons scenario where individual rational behavior leads to collectively irrational outcomes. This fundamental recognition has catalyzed the development of two primary regulatory approaches: direct price instruments through carbon taxation and quantity-based instruments through emissions trading systems. Both mechanisms operate on the principle of price discovery, albeit through different pathways that reflect distinct philosophical approaches to environmental regulation and market intervention.

Carbon taxation represents the most direct application of Pigouvian taxation theory, where governments impose levies proportional to the carbon content of fossil fuels or the emissions generated by industrial processes. This approach provides what economists term "price certainty" by establishing predetermined costs for carbon emissions, enabling enterprises to incorporate these expenses into long-term investment planning and operational decision-making frameworks [9]. The theoretical appeal of carbon taxation lies in its administrative simplicity and immediate price signal transmission, characteristics that align with neoclassical economic assumptions regarding rational actors responding predictably to price incentives. However, this approach exhibits what scholars have identified as "quantity uncertainty", where the ultimate level of emission reductions remains contingent upon market responses to the imposed tax rates rather than predetermined environmental targets.

Conversely, emissions trading systems embody what economists describe as "cap-and-trade" mechanisms, establishing predetermined limits on aggregate emissions while allowing market forces to determine the optimal allocation of emission reduction efforts across participating entities. This approach draws theoretical inspiration from the Coase theorem, which posits that parties can negotiate efficient solutions to externality problems when property rights are clearly defined and transaction costs remain minimal [10]. The theoretical elegance of emissions trading lies in its capacity to achieve predetermined environmental outcomes at minimum economic cost by enabling entities with lower abatement costs to undertake proportionally greater emission reductions while selling excess allowances to entities facing higher abatement expenses.

The carbon trading mechanism represents a vanguard of emission reduction based on market mechanisms, with the EU ETS serving as the most prominent empirical manifestation of this theoretical framework. Since its launch in 2005, the EU ETS has been continuously optimized and improved, evolving into the world's largest carbon trading market with the longest operating history [11]. This system brings numerous energy-intensive industries within the European Union under its regulatory purview. By setting a stringent cap on the total amount of carbon emissions and allocating carbon emission allowances to enterprises, it has established a comprehensive market value system for carbon emissions [10]. Under this system, enterprises that successfully control their emissions within allocated allowances through energy conservation and emission reduction measures can sell remaining allowances in the market and generate profits. Conversely, entities whose emissions exceed their allowances must purchase additional permits. Based on market supply and demand dynamics, this incentive and restraint mechanism has effectively stimulated enterprises' enthusiasm for proactive emission reduction initiatives, thereby facilitating industries' green and low-carbon transformation.

The theoretical sophistication of carbon pricing mechanisms extends beyond simple price-quantity relationships to encompass complex behavioral dynamics that influence strategic decision-making across multiple time horizons. Contemporary research has revealed that carbon pricing effectiveness depends on market participants' expectations regarding future policy trajectories, technological developments, and regulatory stability [7]. This recognition has prompted scholars to examine carbon pricing through the lens of behavioral economics, acknowledging that real-world decision-makers exhibit bounded rationality, loss aversion, and temporal discounting patterns that deviate from theoretical assumptions of perfect rationality and complete information.

Furthermore, the integration of carbon pricing mechanisms with EM operations introduces additional theoretical complexities that necessitate sophisticated analytical frameworks capable of capturing multi-agent strategic interactions. The research conducted by Narassimhan et al. demonstrates that carbon pricing effectiveness varies significantly across different market structures, regulatory frameworks, and technological contexts [10]. These findings underscore the importance of understanding carbon pricing not merely as an isolated policy instrument but as a component of broader institutional arrangements that shape competitive dynamics and investment incentives within energy systems.

The theoretical foundations of carbon pricing also encompass critical considerations regarding distributional effects and equity implications that extend beyond pure efficiency calculations. Research examining income distribution effects reveals that carbon pricing mechanisms can exhibit regressive characteristics, imposing proportionally greater burdens on lower-income households and small enterprises with limited capacity for technological adaptation [12]. This recognition has prompted theoretical developments in environmental justice scholarship that seek to design carbon pricing mechanisms capable of achieving environmental objectives while maintaining social equity and economic fairness.

The temporal dimension of carbon pricing theory presents additional challenges related to dynamic efficiency and intertemporal optimization. Unlike static economic models that assume instantaneous adjustment to price signals, carbon pricing operates within complex systems characterized by significant capital stock turnover periods, technological learning curves, and institutional adaptation processes. This temporal complexity necessitates theoretical frameworks that can accommodate path dependence, technological lock-in effects, and the gradual evolution of market structures in response to sustained policy interventions.

Recent theoretical advances have also emphasized the importance of understanding carbon pricing within broader institutional economics and political economy frameworks. The effectiveness of carbon pricing mechanisms depends not only upon their technical design characteristics but also upon the broader governance structures, enforcement capabilities, and social acceptance that determine their implementation and long-term sustainability. This institutional perspective highlights the need for theoretical approaches to capture the co-evolution of carbon pricing policies with broader energy market institutions, regulatory frameworks, and societal values.

These theoretical foundations establish the conceptual groundwork for understanding how carbon pricing mechanisms interact with strategic behaviors in EMs, creating complex dynamics that require evolutionary game-theoretic approaches to fully comprehend the long-term adaptation processes that characterize energy system transitions under carbon constraints.

2.2. Comparative Analysis of Carbon Tax and Emissions Trading Systems

China's carbon trading market is also developing steadily. Since the start of trading in 2021, key emission units in the power generation industry have been incorporated into it. In the future, more energy-intensive industries such as steel, cement, and the chemical industries will gradually be included. This move is playing an increasingly prominent role in promoting the green and low-carbon transformation of the economy [12]. On the other hand, the carbon tax mechanism directly taxes the carbon content or carbon emissions of fossil fuels instead of setting permitted emission levels [9]. This mechanism internalizes the external costs of carbon emissions, thereby increasing enterprises' carbon emission costs and prompting them to reduce carbon emissions, with the aim of slowing down global warming. Unlike the carbon trading mechanism, the carbon tax mechanism features clear costs. Enterprises can clearly know the tax fees for each unit of carbon emissions, and the price is relatively stable, with strong certainty and predictability, which is conducive to enterprises' cost accounting and long-term planning. However, it is difficult to adjust the price flexibly according to market supply and demand and emission reduction targets, and it cannot directly control the total amount of emissions, so the certainty of the amount of emission reduction is relatively weak. The specific comparison is shown in Table 1. This table reveals fundamental trade-offs inherent in carbon pricing mechanism design that have significant implications for energy market transformation strategies. The comparative analysis demonstrates that no single mechanism provides optimal outcomes across all evaluation dimensions, necessitating careful consideration of jurisdictional priorities and institutional capabilities.

Table 1. Comprehensive comparison of carbon pricing mechanisms: design principles and market impacts.

Mechanism Characteristic	Carbon Tax System	Emissions Trading System (ETS)	Hybrid Approach	Supporting References
Regulatory Framework	Direct tax on carbon content or emissions of fossil fuels with government-set rates	Cap-and-trade system with total emission limits and tradeable allowances	Combined tax and trading mechanisms with coordinated policy instruments	[7,8,10,13,14]
Price Formation Mechanism	Fixed government-set price providing cost certainty for compliance planning	Market-determined prices based on supply-demand dynamics with price volatility	Dual pricing system with tax floor and trading ceiling, creating price corridors	[7,10,12]
Cost Predictability	High predictability enabling long-term investment planning and cost forecasting	Lower predictability due to market volatility requires sophisticated risk management	Moderate predictability with bounded price ranges provides planning certainty	[7,13,15]
Administrative Complexity	Low complexity with straightforward tax collection and enforcement mechanisms	High complexity requiring monitoring, reporting, verification, and trading infrastructure	Moderate complexity balancing administrative burden with policy effectiveness	[8,10]
Revenue Generation	Direct government revenue through tax collection, enabling policy funding	Revenue depends on the allowance allocation method and trading profits	Diversified revenue streams through both tax collection and allowance auctions	[12,13]
Distributional Effects	Uniform cost impact across all emitters regardless of abatement cost differences	Efficient allocation allowing low-cost abaters to reduce emissions for high-cost emitters	Targeted impact enabling differentiated treatment based on sector characteristics	[10,14,15]

The carbon tax system emerges as the most administratively efficient approach with superior cost predictability, making it particularly suitable for developing economies with limited regulatory infrastructure. However, its uniform cost impact creates potentially regressive distributional effects that may undermine political sustainability. The emissions trading system offers superior allocative efficiency through market-based price formation, but requires sophisticated institutional infrastructure that may exceed the capabilities of many jurisdictions.

The hybrid approach presents a compelling compromise that addresses the primary limitations of pure mechanisms while introducing manageable complexity increases. The price corridor framework provided by combining tax floors with trading ceilings offers an innovative solution to the volatility concerns that have plagued standalone ETS implementations while preserving market efficiency benefits.

Most significantly, the distributional effects dimension reveals that mechanism choice has profound implications for industrial competitiveness and just transition considerations. The efficient allocation properties of ETS mechanisms enable targeted support for high-abatement-cost industries while maintaining overall emission reduction effectiveness. This insight suggests hybrid approaches may be essential for managing the political economy challenges of carbon pricing implementation, particularly in jurisdictions with significant industrial exposure to international competition.

In terms of the principle, the carbon tax mechanism in Table 1 follows the "polluter pays" principle, and its core lies in transforming the external costs generated by carbon emissions into the internal production costs of enterprises.

Take a thermal power generation enterprise as an example. The imposition of a carbon tax increases the power generation cost. In order to maintain profits and competitiveness, the enterprise will take measures such as improving power generation efficiency or switching to clean energy power generation to reduce carbon emissions and carbon emission costs. The carbon emissions trading mechanism is constructed based on the Coase theorem. After the government sets the cap on the total amount of emissions and allocates the allowances, enterprises can trade the allowances among themselves [7]. Under this mechanism, enterprises with low emission reduction costs can obtain economic benefits by selling the excess allowances, while enterprises with high emission reduction costs need to purchase the allowances, thus promoting the overall emission reduction in the market.

2.3. Strategic Bidding Behaviors under Carbon Pricing Constraints

The two mechanisms also have different impacts on different enterprises. The carbon tax mechanism has a greater impact on small and medium-sized energy-intensive enterprises. These enterprises have limited profit margins, and the increased costs brought about by the carbon tax may become a heavy burden [15]. To cope with the cost pressure, enterprises either have to invest funds in energy conservation and emission reduction technological transformation or face the risk of being eliminated from the market. The carbon emissions trading mechanism provides more flexibility for large enterprises. With their financial and technological advantages, large enterprises are more proactive in emission reduction. They can not only achieve emission reduction by investing in low-carbon technologies and make profits by selling the excess allowances, but also purchase allowances from the market when the allowances are insufficient to maintain the normal production and operation of the enterprises.

The implementation of the carbon pricing mechanism has had quite different impacts on different types of power generation enterprises. For traditional power generation enterprises mainly relying on fossil energy such as coal, carbon pricing is undoubtedly a double-edged sword. On the one hand, carbon pricing significantly increases their power generation costs because traditional power generation enterprises need to pay additional fees for carbon emissions during production. On the other hand, carbon pricing also brings pressure and motivation for transforming and upgrading traditional power generation enterprises. To survive and develop in the fierce market competition, traditional power generation enterprises have to increase their investment in the research, development, and application of energy conservation and emission reduction technologies. They also have to reduce the carbon emission costs through technological innovation to achieve the green and low-carbon transformation. For renewable energy enterprises, carbon pricing is a major development opportunity. Since renewable energy generates almost no carbon emissions during the production process, it has an obvious cost advantage under the carbon pricing mechanism compared with traditional power generation enterprises. This cost advantage makes renewable energy enterprises more competitive in the market competition and enables them to obtain power generation opportunities and market share more easily. With the continuous market share expansion, renewable energy enterprises will have more funds to invest in technological research and development and industrial expansion, further promoting the progress of renewable energy technologies and the growth of the industrial scale.

(1) Carbon Pricing Impact on Fossil-Based Power Generation

The implementation of carbon pricing mechanisms fundamentally alters the operational economics of fossil fuel-based power generation by internalizing previously externalized environmental costs. Research by Liu et al. (2021) demonstrates that thermal power enterprises face critical strategic decisions regarding carbon asset management, with options ranging from technological upgrades to market exit under escalating carbon prices [16]. The cost burden imposed by carbon pricing creates immediate pressure for efficiency improvements and long-term incentives for clean technology adoption, as documented in the comprehensive analysis by Chang et al. (2024) examining green innovation responses among heavily polluting enterprises [17].

(2) Carbon Pricing Effects on Renewable Energy Providers

Renewable energy enterprises experience significant competitive advantages under carbon pricing regimes due to minimal operational emissions. The research conducted by Wang et al. (2024) reveals that government subsidies combined with carbon pricing create powerful synergies that enhance renewable energy auction competitiveness [18]. This dual advantage enables renewable energy providers to expand market share while investing additional resources in technological advancement and capacity expansion, creating positive feedback loops that accelerate clean energy deployment.

(3) Market Clearing and Pricing Mechanism Analysis

The interaction between carbon pricing and EM clearing mechanisms introduces complex dynamics that influence both short-term operations and long-term strategic planning. Liu et al. (2022) demonstrate that strategic bidding behaviors under marginal cost pricing and pay-as-bid mechanisms exhibit differential sensitivities to carbon price fluctuations [19]. The two-tier bidding model developed by Wang et al. (2024) illustrates how multi-stage carbon incentive mechanisms can optimize market clearing while promoting low-carbon generation [20].

(4) Strategic Bidding Optimization under Carbon Constraints

Power generation enterprises must fundamentally reconsider their bidding strategies when carbon pricing alters traditional cost structures. The evolutionary game framework presented by Cheng et al. (2022) provides insights into long-term strategic adaptation under different market clearing mechanisms [21]. Tang et al. (2021) further demonstrate how market liberalization degrees influence the evolutionary dynamics of generator bidding strategies, revealing critical relationships between regulatory frameworks and strategic behaviors [22].

2.4. Integrated Market Dynamics and Policy Implications

Based on the above, Table 2 provides a comprehensive analysis of the key aspects discussed in this section on carbon pricing mechanisms and EM bidding, focusing on the different ways carbon pricing and bidding mechanisms affect power generation enterprises. Under different pricing and bidding strategies, it systematically evaluates the implications for various stakeholders, including fossil fuel and renewable energy companies.

(i). Impact on Fossil and Renewable Energy Enterprises: The table clearly highlights the dual role of carbon pricing. For fossil fuel-based power plants, carbon pricing increases operational costs but simultaneously pressures companies to innovate and adopt cleaner technologies. On the other hand, renewable energy companies benefit from a clear cost advantage, enabling them to grow rapidly and increase their market share. This dynamic aligns with the need for balanced policies that promote clean energy development while supporting traditional energy firms' transitions.

(ii). Bidding Mechanisms and Market Effects: Both Marginal Cost Pricing (MCP) and Pay-as-Bid (PAB) mechanisms significantly influence energy market operations. MCP ensures price adjustments based on the marginal cost of generation, providing real-time market efficiency. Meanwhile, PAB allows for greater strategic pricing flexibility, encouraging competitive behaviors among power generation enterprises. The policy implications are clear: mechanisms like MCP need refinement to reflect actual market conditions better, while PAB requires balance to avoid monopolistic practices.

(iii). Technological and Market Adaptation: Both market mechanisms encourage technological innovations—fossil fuel companies must innovate to lower their carbon emission costs, while renewable energy firms expand their capacity through further research and development. This technological progress is crucial to supporting the broader low-carbon transition. The analysis underscores the need for policies that stimulate innovation across both sectors, ensuring competitiveness in the evolving market.

(iv). Future Research Directions: This table also suggests several key avenues for future research. There is a need to investigate how carbon pricing can be optimized to support energy transitions, integrate EGT with market strategies, and create adaptive policy frameworks that respond to fluctuating energy demands.

In conclusion, Table 2 illustrates the complex, interdependent relationships between carbon pricing, energy market bidding mechanisms, and the strategies adopted by different energy enterprises. These interactions provide valuable insights for policymakers looking to refine carbon pricing mechanisms and optimize bidding strategies to foster a sustainable energy future.

Table 2. Analysis of the impact of carbon pricing mechanisms and EM bidding strategies on energy market dynamics.

Aspect	Description	Effect on Market Participants	Implications for Policy	Technological Implications	Potential Research Directions	References
Impact of Carbon Pricing on Fossil-based Power Generation	Carbon pricing raises costs for fossil fuel-based power generation, increasing operational expenses due to carbon emission fees.	Increases costs for fossil fuel power plants, driving technological innovation for emission reduction.	Suggests the need for policies that mitigate the cost burden on fossil fuel power plants while incentivizing cleaner technologies.	Fossil fuel firms must invest in cleaner technologies to reduce carbon emissions and remain competitive in the market.	Further investigation into the effectiveness of carbon pricing mechanisms in fostering a sustainable energy transition for traditional power generation.	[16,17]
Effect of Carbon Pricing on Renewable Energy Providers	Renewable energy firms gain a cost advantage due to minimal carbon emissions, enhancing their market competitiveness under carbon pricing.	Provides a competitive edge, enabling easier market share acquisition and more funds for technological advancements.	Highlights the potential for renewable energy to thrive under carbon pricing, necessitating supportive policies for continued growth.	Renewable energy firms can further reduce costs and expand market share by investing in research and development.	Exploring how renewable energy firms can use carbon pricing as an opportunity to scale their operations and accelerate technological innovation.	[18,23]
Marginal Cost Pricing (MCP) Mechanism	MCP adjusts electricity prices based on the marginal cost of the last unit of power generation meeting market demand, reflecting real-time cost fluctuations.	Guides power generation planning, enhancing operational efficiency by adapting to demand changes.	Indicates the importance of a well-designed MCP framework to reflect market conditions accurately and optimize energy production.	MCP drives technological improvements to optimize production costs and ensure competitiveness in energy markets.	Studies on improving MCP mechanisms to ensure they reflect true market costs and optimize energy production across different sectors.	[19,20]
Pay-as-Bid (PAB) Mechanism	PAB allows power generation enterprises to set their own prices, stimulating competition and encouraging cost reduction to maximize economic benefits.	Encourages competitive behavior, improving efficiency, and reducing costs to gain economic advantage.	Suggests the importance of balancing PAB mechanisms with market demand to ensure fair competition and prevent monopolies.	PAB encourages firms to develop efficient bidding strategies by focusing on cost reduction and market analysis.	Research on balancing the PAB system to maintain fair competition and avoid market manipulation.	[19,21]
Bidding Strategy Optimization for Power Generation Enterprises	Enterprises must optimize production technologies, reduce costs, and assess market conditions to strategically bid and secure market share.	Firms are encouraged to improve technological efficiency and strategically adapt to market and cost changes to remain competitive.	Emphasizes the need for policies that promote the technological advancement of power generation enterprises and ensure fair competition.	Optimizing production technologies and cost structures becomes crucial for companies to remain competitive in a dynamic market.	Future work can focus on the integration of EGT to model strategic bidding behaviors in evolving markets.	[21,22]
Impact of Market Demand on Pricing Mechanisms	An increase in market demand prompts investment in additional power generation resources, raising the market clearing price; conversely, a decrease reduces prices.	Market clearing price is dynamically adjusted based on demand, influencing power generation strategies.	Suggests the importance of flexible policy frameworks that can adapt to demand fluctuations and ensure market stability.	Fluctuations in demand require adaptive strategies and technological investments to maintain market competitiveness.	Research on flexible policy structures that allow for real-time market demand adaptation and price adjustment.	[20,24]

As elaborated above, in the EM, the bidding mechanism is the core mechanism determining the allocation of electricity resources and the formation of prices, mainly including the MCP and PAB mechanisms. The bidding mechanism is crucial for the allocation of electricity resources and the formation of prices. The marginal cost pricing mechanism is one of the more widely applied pricing methods. Under this mechanism, the clearing price of the EM is determined by the marginal power generation cost of the generating unit that finally meets the market demand [25]. For example, in the analysis of the role of marginal cost pricing in the transportation field, Ref. [26] points out that the way it adjusts prices according to cost changes and the resulting impacts are consistent with the pricing mechanism in the EM. When the market demand for electricity increases, the power system must invest in additional generation resources to meet the higher demand. However, as more generation resources are deployed, the last resources added often have a higher marginal cost due to factors such as lower energy efficiency and equipment aging. As a result, the market clearing price rises to balance the costs and revenues. Conversely, when electricity demand decreases, the power system reduces investment in generation resources, and less efficient equipment is taken offline. This leads to a decrease in marginal cost and, consequently, a reduction in the market clearing price. This pricing mechanism effectively reflects real-time changes in marginal power production costs, helping power generation companies optimize their generation schedules based on market demand and cost conditions, thereby enhancing the operational efficiency of the EM.

The PAB mechanism gives power generation enterprises greater autonomy in pricing. Enterprises formulate bidding strategies according to their power generation costs, market expectations, and analysis and judgment of their competitors, and the market clearing price is a comprehensive reflection of the bids of all participating power suppliers [19]. This mechanism fully stimulates the market competition awareness of enterprises, encourages enterprises to improve their bidding competitiveness by reducing costs and improving efficiency, and obtains more power generation shares and economic benefits.

Different bidding mechanisms have a profound impact on the participants in the EM. Under the marginal cost pricing mechanism, power generation enterprises need to continuously optimize their production technologies and reduce the marginal power generation cost to increase their revenues. As pointed out in Ref. [27], in the auction mechanism of the EM, suppliers adjust their bidding strategies to maximize their profits. This is similar to the considerations of power generation enterprises on costs and revenues under the marginal cost pricing mechanism. Power generation enterprises need to continuously optimize their production technologies to reduce costs and enhance their competitiveness in the market, just as suppliers adjust their strategies in the auction mechanism. In the PAB mechanism, power generation enterprises not only need to pay attention to the power generation cost, but also need to analyze aspects such as market supply and demand and the bids of their competitors, to formulate a reasonable bidding strategy and maximize their interests.

There is a close coupling relationship between carbon pricing and EM bidding. The carbon pricing mechanism affects the cost structure of power generation enterprises and thus changes their strategies in the EM bidding. However, this coupling extends beyond simple cost adjustments to encompass complex temporal and cross-market dynamics that fundamentally reshape both carbon and EM operations.

The linkage effects between carbon markets and day-ahead EMs manifest through multiple interconnected channels. First, carbon allowance prices directly influence generation cost structures, propagating through day-ahead market bidding strategies and clearing prices. Second, day-ahead market dispatch decisions determine actual emissions and carbon allowance demand, creating feedback loops that affect carbon market prices. Third, temporal arbitrage opportunities emerge as market participants optimize across both carbon allowance procurement and electricity generation scheduling horizons.

Based on the above, Table 3 provides a comprehensive framework for analyzing these carbon-electricity market linkage effects across multiple dimensions. This comprehensive linkage analysis reveals several critical insights. The cost transmission channel demonstrates that carbon pricing effects are not uniform across time periods, with peak electricity demand periods experiencing amplified carbon price impacts due to the activation of higher-emission generation units. The dispatch optimization dimension shows that carbon markets fundamentally alter EM merit orders, creating systematic shifts in generation patterns that feedback into carbon allowance demand. Investment signals generated through carbon markets create long-term structural changes in EM dynamics, while short-term risk management strategies create complex temporal coupling between the markets.

Table 3. Comprehensive analysis of carbon-electricity market linkage effects.

Linkage Dimension	Carbon Market Impact	Day-Ahead Electricity Market Impact	Temporal Coupling	Policy Implications
Cost Transmission	Carbon prices increase marginal costs for fossil fuel generators by 15–45% depending on emission factors.	Higher generation costs lead to increased electricity prices, with peak hour impacts of 20–60% price elevation.	Real-time carbon price volatility creates hourly cost variations affecting day-ahead bidding strategies.	Carbon price volatility dampening mechanisms are needed to ensure EM stability.
Dispatch Optimization	Expected dispatch patterns influence carbon allowance procurement strategies and forward contracting.	Carbon costs alter merit order dispatch, increasing renewable energy penetration by 10–25% in high carbon price scenarios.	Day-ahead market clearing determines next-day emissions, affecting intraday carbon allowance trading.	Coordinated market clearing mechanisms are required to optimize cross-market efficiency.
Investment Signals	Long-term carbon price expectations drive generation investment decisions toward low-carbon technologies	Day-ahead market revenue streams influence generation asset valuation and investment timing	Investment cycles in both markets create multi-year coupling effects on technology deployment.	Long-term carbon price trajectories must be coordinated with EM design evolution.
Risk Management	Carbon price hedging strategies affect EM bidding behavior and risk premiums.	Day-ahead price volatility influences carbon portfolio management and emission allowance holding strategies.	Cross-market hedging creates temporal dependencies between carbon futures and electricity forward markets.	Integrated risk management frameworks are needed for market participants operating across both markets.
Market Liquidity	Electricity sector participation represents 40–60% of carbon market trading volume in major ETS systems.	Carbon cost uncertainty reduces day-ahead market liquidity and increases bid-ask spreads during volatile periods.	Intraday trading patterns in carbon markets correlate with day-ahead EM clearing outcomes.	Market microstructure design should consider cross-market liquidity provision and market making incentives.

The temporal coupling effects are particularly significant, as they create dynamic interdependencies that cannot be captured through static analysis. Day-ahead EM outcomes directly determine the emission profiles that drive carbon allowance demand, while carbon market price expectations influence EM bidding behavior. This creates a continuous feedback loop that requires sophisticated modeling approaches to capture the system dynamics fully.

Policy implications emerging from this analysis emphasize the need for coordinated market governance structures that recognize these interdependencies. Traditional approaches that treat carbon and EMs independently may create unintended consequences and suboptimal outcomes across both domains. Ref. [20] mentions that carbon pricing will increase the carbon emission costs of thermal power units, and renewable energy units such as wind power and solar energy will be compensated due to their clean energy attributes, affecting the structural transformation of the power generation side. Under the carbon trading mechanism, enterprises with low carbon emission costs have more advantages in bidding. They can participate in the competition in the EM at a more flexible price with their excess carbon emission allowances. The carbon tax mechanism directly increases the costs of power generation enterprises, prompting them to consider costs and revenues more carefully when bidding. At the same time, the bidding results of the EM will also be fed back to the field of carbon pricing. When the EM price changes due to the supply and demand relationship, it will affect the production scale and carbon emission levels of power generation enterprises and thus affect the demand for and price of allowances in the carbon market. This two-way interaction makes carbon pricing and EM bidding form an organic whole, with the day-ahead EM serving as the primary transmission mechanism through which carbon pricing signals propagate to real-time generation decisions and emission outcomes, jointly affecting the development of the electricity industry and the control of carbon emissions.

Since renewable energy power generation enterprises have a cost advantage under the carbon pricing mechanism, their entry will increase the electricity supply in the market, ease the upward pressure on market prices, and also help to reduce the carbon emission levels of the entire EM. This dynamic interaction between carbon pricing and the market clearing price continuously adjusts the supply and demand structure and price system of the EM. It promotes the EM to develop in a sustainable direction.

3. Game Theory and Evolutionary Dynamics in Energy Markets

3.1. Foundations of Game Theory in Bid Design

Game theory provides a mathematical framework for analyzing strategic interactions among rational decision-makers, making it particularly relevant for understanding competitive bidding in EMs. In the context of energy market bid design, game theory addresses fundamental questions about how market participants formulate bidding strategies when their payoffs depend not only on their own actions but also on the strategic choices of competitors.

Classical game theory applications in bid design typically assume complete rationality, perfect information, and static equilibrium conditions. In EMs, generators submit bids representing their willingness to supply electricity at various price levels, while system operators clear the market by selecting the lowest-cost combination of bids to meet demand. The strategic nature of this process creates a game-theoretic environment where each generator’s optimal bidding strategy depends on anticipated competitor behaviors.

Traditional game-theoretic models of EM bidding include Cournot competition, where generators compete on quantity while treating prices as endogenous variables, and Bertrand competition, where participants compete directly on price. Supply function equilibrium models extend these concepts by allowing generators to submit entire supply curves rather than single price-quantity pairs. These approaches have provided valuable insights into market power, price formation, and strategic behavior in deregulated EMs.

However, classical game theory faces significant limitations when applied to carbon-constrained energy markets. The assumption of complete rationality becomes problematic when market participants face unprecedented policy environments with evolving carbon pricing mechanisms. Perfect information assumptions fail to capture the uncertainty surrounding future carbon prices, technological developments, and regulatory changes. Most critically, static equilibrium concepts cannot adequately represent the dynamic nature of energy transition processes, where market participants continuously adapt their strategies based on observed outcomes and changing environmental conditions.

3.2. Carbon Trading Characteristics and the Need for Evolutionary Approaches

Carbon trading mechanisms introduce unique characteristics that fundamentally alter the strategic landscape of EMs, necessitating analytical approaches that can capture dynamic adaptation and learning processes. These characteristics create compelling justifications for EGT as the appropriate modeling framework.

First, carbon pricing mechanisms generate unprecedented uncertainty in cost structures and competitive positions. Unlike traditional fuel price volatility, carbon prices reflect complex interactions between environmental policy, technological innovation, and market speculation. This uncertainty prevents market participants from forming precise expectations about competitor strategies, violating the perfect information assumptions underlying classical game theory. EGT addresses this limitation by modeling strategy evolution under bounded rationality, where participants adapt based on observed performance rather than complete market knowledge.

Second, the energy transition represents a fundamental shift in technological and economic paradigms, creating conditions where historical experience provides limited guidance for future strategic decisions. Market participants must experiment with new technologies, business models, and bidding strategies while learning from both their own experiences and competitor behaviors. This learning process aligns naturally with EGT's emphasis on strategy adaptation through imitation of successful behaviors and mutation of existing strategies.

Third, carbon trading markets exhibit strong path-dependence effects, where early strategic choices significantly influence long-term competitive positions and market structures. The irreversible nature of infrastructure investments in renewable energy technologies or carbon capture systems creates strategic complementarities that evolve over time. EGT captures these dynamics through replicator dynamics that track the changing frequency of different strategies in the population.

Fourth, policy interventions in carbon markets often trigger cascading effects that propagate through the market over extended time periods. Subsidy programs, penalty mechanisms, and regulatory changes create shifting competitive landscapes that require continuous strategic adaptation. Traditional static equilibrium concepts cannot capture these adjustment processes, while EGT provides tools for analyzing convergence to new equilibria following policy shocks.

3.3. EGT: Mathematical Framework and Core Concepts

Evolutionary game theory (EGT) extends classical game theory by incorporating dynamic strategy evolution based on differential success rates rather than perfect rationality assumptions. The mathematical foundation rests on the replicator dynamic equation, which describes how the frequency of different strategies changes over time based on their relative performance.

Consider a population of energy market participants choosing from a set of strategies $S = \{s_1, s_2, \cdots, s_n\}$. Let $x_i(t)$ represent the proportion of the population using strategy s_i at time t, where $\Sigma_i x_i(t) = 1$. The fitness of strategy s_i is given by $f(s_i, x(t))$, representing the expected payoff when the population state is $x(t)$. The average fitness of the population is $\varphi(x(t)) = \Sigma_i x_i(t) \cdot f(s_i, x(t))$. Thus, the replicator dynamic equation governs strategy evolution: $\dot{x}_i = x_i \cdot [f(s_i, x(t)) - \varphi(x(t))]$.

This equation indicates that strategies with above-average fitness increase frequency, while below-average strategies decline. The equilibrium concept in EGT is the evolutionarily stable strategy (ESS), which represents a strategy distribution that cannot be invaded by small populations using alternative strategies.

For carbon-constrained energy markets, the fitness function $f(s_i, x(t))$ incorporates traditional economic payoffs and carbon-related costs and benefits. This creates complex fitness landscapes where renewable energy strategies may have lower immediate payoffs but superior long-term evolutionary stability under rising carbon prices.

3.4. EGT Applications in Power Markets

The EGT integrates traditional game theory with biological evolution theory and analyzes the long-term change trends of individual strategies in a group from the perspective of dynamic evolution. Different from traditional game theory, it assumes that participants are not completely rational but adjust their own behaviors by continuously learning from and imitating the strategies of others. The replicator dynamic equation is its core tool, which is used to describe the dynamic process of the proportion of individuals with different strategies in a population changing with the payoff. In this process, the proportion of high-payoff strategies in the group gradually increases, while low-payoff strategies tend to be eliminated. The ESS reveals the long-term stability of group behavior. When the vast majority of individuals adopt this strategy, it is difficult for small-scale mutant strategies to invade and replace it [28]. The EGT is suitable for analyzing scenarios with multiple agents, bounded rationality, and dynamic evolution. Its advantage lies in being able to better describe the behavior patterns of real individuals and revealing the long-term trends of group behavior through dynamic analysis. The theoretical model is based on assumptions such as individual strategy selection relying on payoff comparison, and the randomness and gradualness of strategy adjustment. Core parameters such as the strategy payoff matrix, the strategy adjustment rate, and the group size jointly determine the evolutionary path and stable state of the system.

The application of EGT to power markets has revealed fundamental insights into long-term market evolution under technological and regulatory change. Unlike static game-theoretic models that focus on immediate equilibrium outcomes, evolutionary approaches illuminate the pathways through which markets transition between different competitive structures.

In the EM, the EGT provides a new perspective and method for analyzing complex systems with multiple agents and multiple strategies. The agents in the EM include traditional power generation enterprises, renewable energy enterprises, grid operators, consumers, etc. Among them, the game between traditional power generation enterprises and renewable energy enterprises is an important driving force for market evolution. There are differences in cost structures and technical characteristics between these two types of enterprises, and the EGT can be used to analyze their strategic choices in different policy environments and the impacts on the market structure. In addition, the agents in the EM face a variety of strategic choices, such as bidding strategies, carbon emission reduction strategies, and green certificate trading strategies.

Early applications in power markets focused on generation technology choice, where utilities must decide between investments in conventional fossil fuel plants versus renewable energy technologies. Evolutionary models demonstrate how carbon pricing mechanisms can trigger tipping points where renewable strategies become evolutionarily dominant, even when they initially have higher costs. These transitions exhibit hysteresis effects, where the path to renewable dominance depends on the speed and magnitude of carbon price increases.

The EGT can analyze the long-term evolutionary trends of these strategies and their impacts on market efficiency and environmental benefits. For example, for complex systems with multi-agent interactions, Ref. [29] constructs a dynamic evolutionary game model covering multiple agents, providing a theoretical basis for various stakeholders to explore optimal strategies. Regarding the interest coordination between renewable energy and traditional energy enterprises, Ref. [30] takes into account the green certificate price and carbon emission reduction costs and proposes reliable strategies. Besides, Ref. [31] analyzes the strategic behaviors of carbon trading enterprises through an evolutionary game.

Market structure evolution represents another significant application area. EGT explains how deregulated EMs evolve from concentrated oligopolies dominated by large thermal generators toward more fragmented structures with numerous renewable energy producers. This structural evolution emerges naturally from differential growth rates between technology types rather than regulatory mandates.

Strategic bidding behavior in evolutionary contexts differs fundamentally from static optimization approaches. Market participants develop bidding heuristics through trial-and-error learning processes, gradually converging toward strategies that perform well against the evolving population of competitor strategies. This creates complex co-evolutionary dynamics where optimal bidding strategies continuously evolve in response to changing competitor behaviors and market conditions.

Moreover, the EM dynamics requires the modeling method to adapt to complex environmental changes. The EGT can better describe the strategic adjustment process of market agents by introducing dynamic equations and stochastic processes. By combining the replicator dynamic equation with the stochastic differential equation, it is possible to analyze the impacts of policy changes, technological progress, and market demand fluctuations on the behaviors of market agents. In this regard, Ref. [32] constructs a stochastic evolutionary game model and uses numerical simulation and the three-party replicator dynamic equation to analyze the impacts of the Trading of Green Certificates (TGC) on the decision-making behaviors of the three parties, providing valuable insights for policy-making. Ref. [33] predicts the payoffs and strategic choices of enterprises by calculating their replicator dynamic equations. Ref. [21] designs an evolutionary game analysis program to describe the properties of local dynamics in the dynamic process of the system, helping the groups participating in bidding to correct and improve their behaviors continuously. Table 4 summarizes the applications of EGT in EMs.

Recent research has extended EGT to multi-market interactions, where participants simultaneously compete in EMs, capacity markets, and carbon trading systems. These applications reveal how policy design in one market can generate unintended consequences in related markets through evolutionary spillover effects.

Table 4. Systematic analysis of key literature in EGT and energy market applications.

Reference	Research Focus	Methodological Approach	Carbon Pricing Integration	Key Findings and Limitations
Narassimhan et al. (2018) [10]	Emissions trading systems review	Comparative policy analysis	Comprehensive ETS examination across regions	Thorough policy evaluation; lacks strategic interaction modeling
Wang et al. (2024) [20]	Multi-stage carbon joint incentive clearing	Two-tier bidding model	Coupled electricity-carbon market integration	Advanced market coupling approach; limited evolutionary dynamics
Wettergren (2023) [28]	Replicator dynamics of evolutionary games	Mathematical analysis of cost-benefit delays	General framework without energy focus	Establishes a theoretical foundation; lacks energy market application
Fan et al. (2024) [29]	Carbon trading market equilibrium	Tripartite evolutionary game perspective	Central focus on carbon market dynamics	Demonstrates game theory effectiveness; limited bidding strategy analysis
Wu et al. (2023) [30]	Supply chain coordination under a renewable quota	Stackelberg game comparing decision types	Renewable energy quota system integration	Effective supply chain optimization; insufficient market-wide analysis
Wu et al. (2024) [31]	Enterprise energy behaviors in carbon trading	Benefit-cost evolutionary game framework	Direct carbon trading impact assessment	Reveals trading behavior patterns; limited policy optimization insights
Teng et al. (2025) [32]	Trading strategies under renewable portfolio standards	Stochastic evolutionary game with noise simulation	Renewable energy certificate market focus	Advanced stochastic modeling; narrow scope on specific trading mechanisms
He et al. (2023) [33]	Chinese Certified Emission Reduction promotion	Tripartite evolutionary game model	CCER program and carbon market integration	Comprehensive policy analysis; limited international applicability
Cheng et al. (2022) [21]	Strategic long-term bidding in deregulated markets	Two-population n-strategy evolutionary game	Multiple market clearing mechanisms	Innovative bidding strategy framework; minimal carbon pricing consideration
Reka et al. (2024) [34]	Machine learning in demand response	Big data analytics and AI applications	Privacy and security considerations	Technological advancement focus; insufficient game-theoretic integration

As summarized in Table 4, the systematic examination of existing literature reveals several critical insights regarding the current state of EGT applications in energy markets under carbon constraints. The theoretical foundations established by [28] provide essential mathematical frameworks for understanding replicator dynamics, yet these general approaches require substantial adaptation for energy market contexts. The carbon trading applications demonstrated by [29,31] successfully illustrate the effectiveness of evolutionary game approaches in capturing market dynamics, but their analyses remain concentrated on specific market segments without comprehensive integration of bidding strategies and policy optimization.

The stochastic modeling innovations introduced by [32] represent significant methodological advances that address uncertainty in renewable energy markets, while the policy-focused analyses by [33] demonstrate the practical applicability of evolutionary approaches for regulatory design. However, these studies exhibit limited scope regarding comprehensive market-wide analysis and international policy transferability. The strategic bidding framework developed by [21] provides valuable insights into long-term market evolution, yet lacks sufficient integration with carbon pricing mechanisms that fundamentally alter competitive dynamics.

The comparative policy analysis by [10] offers a comprehensive understanding of emissions trading systems but fails to incorporate strategic interaction modeling that captures behavioral adaptation processes. The advanced market coupling approach presented by [20] demonstrates sophisticated integration of electricity and carbon markets, yet overlooks evolutionary dynamics that govern long-term strategic adaptation. Finally, the technological perspectives provided by [34] highlight emerging opportunities for integrating machine learning with energy market analysis, but insufficient attention to game-theoretic foundations limits their applicability for strategic behavior modeling.

This literature synthesis reveals fundamental gaps in comprehensive frameworks that simultaneously address evolutionary strategic dynamics, carbon pricing mechanisms, and policy optimization, thereby establishing the necessity for our integrated review approach.

In addition, simulation methods based on intelligent algorithms, such as genetic algorithms and particle swarm optimization, are also widely applied to the solution and analysis of evolutionary game models. Future research can integrate multi-agent modeling and real-time data-driven technologies to construct a digital twin system that is closer to the real market ecology, promoting the game theory in the EM to leap from explaining phenomena to predicting decisions.

3.5. Evolutionary Dynamics under Carbon Pricing Mechanisms

Carbon pricing mechanisms fundamentally alter the evolutionary dynamics of power markets by introducing new selection pressures that favor low-carbon strategies. The strength and stability of these selection pressures depend critically on carbon price levels, volatility, and credibility of long-term policy commitments.

Under low carbon prices, evolutionary dynamics may converge to mixed equilibria where fossil fuel and renewable strategies coexist in stable proportions. The stability of these mixed equilibria depends on the precise balance between carbon costs and technology cost differentials. Small changes in carbon prices can trigger dramatic shifts in equilibrium strategy distributions, demonstrating the importance of policy design for market evolution outcomes.

High carbon prices create strong selection pressures favoring renewable energy strategies, potentially leading to rapid evolutionary convergence toward low-carbon equilibria. However, the transition speed depends on factors such as capital stock turnover rates, learning curve effects, and infrastructure complementarities. EGT provides tools for analyzing these transition dynamics and predicting convergence timeframes under different policy scenarios.

Carbon price volatility introduces additional complexity by creating time-varying fitness landscapes where optimal strategies change continuously. This volatility can prevent convergence to stable equilibria, instead generating persistent evolutionary cycles or chaotic dynamics. Market participants must balance exploiting current profitable strategies against exploring alternatives that may become advantageous under different carbon price regimes.

Policy credibility emerges as a crucial factor determining evolutionary outcomes. When market participants doubt the long-term sustainability of carbon pricing policies, they may maintain fossil fuel strategies despite temporarily adverse fitness differentials. EGT captures these effects through discounted fitness functions that weight near-term payoffs more heavily than uncertain future benefits.

As summarized in Table 5, this comparative analysis reveals why EGT emerges as the superior theoretical framework for modeling carbon-constrained energy markets. The table systematically evaluates five major game-theoretic approaches across critical dimensions that determine their applicability to carbon trading environments.

Table 5. Comparative analysis of game theory approaches in carbon-constrained energy markets.

Theoretical Framework	Information Requirements	Rationality Assumptions	Temporal Scope	Carbon Market Suitability	Policy Adaptation Capability
Classical Game Theory	Perfect/complete information	Full rationality	Static equilibrium	Limited—fails under price volatility	Poor—requires resolving for policy changes
Bayesian Game Theory	Incomplete but known distributions	Rational Bayesian updating	Static with uncertainty	Moderate—handles some uncertainty	Moderate—requires new prior distributions
Repeated Game Theory	Perfect recall of history	Perfect rationality with reputation	Multi-period static	Moderate—captures some dynamics	Limited—strategy sets remain fixed
EGT	Bounded/local information	Bounded rationality with learning	Dynamic evolution	High—naturally handles volatility	Excellent—continuous adaptation to policy changes
Mean Field Games	Statistical information only	Rational representative agent	Dynamic equilibrium	Moderate—limited heterogeneity	Good—can incorporate policy parameters

Despite its mathematical elegance, classical game theory demonstrates fundamental inadequacies for carbon market analysis. The perfect information requirement becomes unrealistic given the unprecedented uncertainty surrounding carbon price evolution, technological breakthroughs, and policy sustainability. The static equilibrium focus cannot capture the dynamic transition processes that characterize energy market transformation under carbon constraints.

Bayesian game theory offers marginal improvements by accommodating uncertainty through probability distributions, yet it retains the rational optimization framework that proves problematic when market participants face novel strategic environments without historical precedents. The requirement for known probability distributions becomes particularly problematic in carbon markets, where structural breaks and policy innovations create non-stationary environments.

Repeated game theory captures some temporal dynamics through reputation mechanisms and trigger strategies, but maintains fixed strategy sets that cannot evolve with changing technological and regulatory landscapes. This limitation proves critical in carbon markets where innovation continuously expands the available strategic options.

EGT demonstrates clear superiority across all evaluation criteria. Its bounded rationality assumptions align with observed behavior in uncertain environments, while the dynamic evolution framework naturally accommodates the continuous adaptation required in carbon-constrained markets. The framework’s ability to handle volatile carbon prices and adapt to policy changes makes it uniquely suited for energy transition analysis.

Mean field games offer sophisticated mathematical tools for large-population interactions but assume rational representative agents that may not capture the heterogeneous learning processes observed in real energy markets. While useful for certain analytical purposes, they lack the behavioral realism of evolutionary approaches.

This analysis strongly supports the adoption of EGT as the primary analytical framework for understanding strategic behavior in carbon-constrained energy markets.

4. Evolutionary Game Modeling Framework for Strategic Bidding under Carbon Pricing Constraints

4.1. Evolutionary Game Modeling of Strategic Bidding

4.1.1. Bidding Strategy Formulation in Evolutionary Framework

Strategic bidding in carbon-constrained EMs involves generators submitting price-quantity pairs that reflect both immediate profit maximization and long-term evolutionary adaptation. We model this process through an evolutionary game where generators employ different bidding heuristics that evolve based on their relative success over time. Thus, we consider a population of generators $N = \{1, 2, \cdots, n\}$ where each generator i can adopt one of four distinct bidding strategies: $S = \{S_1, S_2, S_3, S_4\}$. Strategy S_1 represents marginal cost bidding where generators bid their true production cost, including carbon expenses. Strategy S_2 involves strategic markup bidding where generators add a percentage markup above marginal cost to capture market power. Strategy S_3 denotes carbon-adjusted bidding where generators incorporate expected future carbon price trends into current bids. Strategy S_4 represents environmental premium bidding where low-carbon generators bid slightly above marginal cost to capture green value.

Let $x_j(t)$ represent the fraction of generators using strategy S_j at time t, where $\Sigma_j\, x_j(t) = 1$. The bidding function for a generator using strategy S_j is defined as:

$$b_j(MC_i, C_t, x(t)) = \alpha_j \cdot MC_i + \beta_j \cdot C_t \cdot E_i + \gamma_j \cdot \mu(x(t)) \tag{1}$$

where MC_i is generator i's marginal cost, C_t represents the current carbon price, E_i denotes emission intensity, and $\mu(x(t))$ captures strategic interactions based on the population strategy distribution. The parameters α_j, β_j, γ_j are strategy-specific coefficients that determine bidding behavior.

4.1.2. Market Clearing and Dispatch Mechanism

The EM operates through a uniform price auction where generators submit bids and the system operator selects the lowest-cost combination to meet demand. Under carbon pricing, the merit order ranking depends on both generation costs and carbon expenses, creating complex interdependencies between bidding strategies and dispatch outcomes.

The market clearing price $P(t)$ emerges from the intersection of aggregate supply and demand:

$$P(t) = b_k(MC_k, C_t, x(t)) \tag{2}$$

where generator k represents the marginal unit that clears the market. The dispatch quantity for generator i using strategy S_j is determined by:

$$q_{i,j}(t) = D_i(b_j(MC_i, C_t, x(t)), P(t)) \cdot I_{\text{dispatch}}(i, j, t) \tag{3}$$

where $D_i(\cdot)$ represents the demand allocation function and I_{dispatch} is an indicator function equal to one if generator i is dispatched and zero otherwise.

4.1.3. Payoff Functions and Fitness Calculation

The evolutionary fitness of each bidding strategy depends on the profit performance of generators employing that strategy. For a generator using strategy S_j, the instantaneous payoff is:

$$\pi_j(x(t), C_t) = q_j(t) \cdot [P(t) - MC_j - C_t \cdot E_j] - FC_j \tag{4}$$

where $q_j(t)$ represents the average dispatch quantity for strategy j users, and FC_j denotes fixed costs. The fitness function incorporates both current profits and adaptation costs:

$$f_j(x(t), C_t) = \pi_j(x(t), C_t) - \kappa_j \cdot |\Delta x_j(t)| \tag{5}$$

where κ_j represents the cost of switching to strategy j and $\Delta x_j(t)$ measures the rate of strategy adoption change.

The relative fitness of strategy j compared to the population average determines its evolutionary success:

$$\Phi_j(x(t), C_t) = f_j(x(t), C_t) - \bar{f}(x(t), C_t) \tag{6}$$

where $\bar{f}(x(t), C_t) = \sum_j x_j(t) \cdot f_j(x(t), C_t)$ represents the average population fitness.

4.1.4. Replicator Dynamics and Solution Derivation

The evolution of bidding strategies follows the replicator dynamic equation:

$$\dot{x}_j = x_j \cdot [f_j(x(t), C_t) - \bar{f}(x(t), C_t)] = x_j \cdot \Phi_j(x(t), C_t) \tag{7}$$

This system of differential equations describes how the frequency of each bidding strategy changes over time based on its relative performance. Strategies that generate above-average fitness increase in frequency, while below-average strategies decline.

To solve this system, we first identify the equilibrium points where $\dot{x}_j = 0$ for all strategies. This occurs when either $x_j = 0$ (strategy j is not used) or $\Phi_j(x(t), C_t) = 0$ (strategy j achieves average fitness). For interior equilibria where multiple strategies coexist, we require:

$$f_j(x(t), C_t) = \bar{f}(x(t), C_t) \text{ for all } j \text{ with } x_j^* > 0 \tag{8}$$

The stability of equilibrium points is determined through linearization analysis. The Jacobian matrix of the replicator system at equilibrium x is:

$$\boldsymbol{J}_{jk}=\frac{\partial\dot{x}_j}{\partial x_k}\Big|_{x^*}=\delta_{jk}\cdot\Phi_j(x^*,C_t)+x_j^*\cdot\left[\frac{\partial f_j}{\partial x_k}-\frac{\partial\bar{f}}{\partial x_k}\right] \tag{9}$$

where δ_{jk} is the Kronecker delta. An equilibrium is locally stable if all eigenvalues of $\boldsymbol{J}$ have negative real parts.

4.1.5. Carbon Price Integration and Dynamic Solution

Carbon price dynamics create time-varying fitness landscapes that influence strategy evolution. We model carbon prices as following a mean-reverting stochastic process:

$$\mathrm{d}C_t=\theta\cdot(\bar{C}-C_t)\mathrm{d}t+\sigma_{\mathrm{C}}\cdot\mathrm{d}W_t \tag{10}$$

where θ represents the speed of mean reversion, $\bar{C}$ is the long-term carbon price target, and σ_{C} controls volatility.

The coupled system of replicator dynamics and carbon price evolution requires numerical solution methods. We employ a predictor-corrector approach:

Step 1 (Prediction): Given current state ($x(t)$, C_t), predict next period values using the Euler method:

$$\begin{cases}\tilde{x}(t+\Delta t)=x(t)+\Delta t\cdot[x_j(t)\cdot\Phi_j(x(t),C_t)]\\ \tilde{C}_{t+\Delta t}=C_t+\theta(\bar{C}-C_t)\Delta t+\sigma_C\sqrt{\Delta t}\cdot\xi_t\end{cases} \tag{11}$$

Step 2 (Correction): Refine predictions using trapezoidal rule:

$$x(t+\Delta t)=x(t)+\frac{\Delta t}{2}[\Phi(x(t),C_t)+\Phi(\tilde{x}(t+\Delta t),\tilde{C}_{t+\Delta t})] \tag{12}$$

This numerical approach enables analysis of long-term strategy evolution under realistic carbon price scenarios.

4.1.6. Equilibrium Characterization and Policy Implications

The evolutionary equilibria exhibit distinct characteristics depending on carbon price levels. At low carbon prices ($C < C_{\mathrm{critical}}$), marginal cost bidding dominates as carbon costs remain small relative to generation cost differences. Above the critical threshold, carbon-adjusted bidding strategies become evolutionarily stable as generators must account for substantial carbon expenses. Thus, the critical carbon price satisfies:

$$C_{\mathrm{critical}}=\frac{MC_{\mathrm{renewable}}-MC_{\mathrm{fossil}}}{E_{\mathrm{fossil}}-E_{\mathrm{renewable}}} \tag{13}$$

Policy interventions can shift these equilibria by altering payoff structures. Renewable energy subsidies effectively reduce $MC_{\mathrm{renewable}}$, lowering C_{critical} and accelerating the transition to low-carbon bidding strategies. Conversely, carbon price volatility can prevent convergence to stable equilibria, creating persistent evolutionary cycling between strategies.

This evolutionary framework provides insights for market design and regulation. Understanding strategy evolution patterns enables policymakers to anticipate market responses to carbon pricing policies and design complementary measures that promote efficient, low-carbon outcomes.

Based on the above, Table 6 summarizes the bidding strategy parameters and evolutionary characteristics. This detailed parameter analysis reveals the intricate mathematical relationships governing bidding strategy evolution in carbon-constrained EMs. The bidding function coefficients demonstrate how different strategies approach cost recovery and profit maximization, with marginal cost bidding maintaining perfect cost recovery while strategic markup bidding incorporates substantial premiums to exploit market power.

The carbon sensitivity parameters highlight the varying degrees to which strategies respond to carbon price signals. Carbon-adjusted bidding strategies exhibit the highest sensitivity coefficients, reflecting their forward-looking approach to carbon cost management. Environmental premium strategies show minimal carbon sensitivity due to their inherently low-carbon characteristics, while strategic markup strategies display variable carbon responses depending on market conditions and competitive pressures.

Table 6. Bidding strategy parameters and evolutionary characteristics.

Strategy Type	Bidding Function Coefficient (*α*)	Carbon Sensitivity (*β*)	Strategic Interaction (*γ*)	Adaptation Cost (*κ*)	Evolutionary Fitness Range
Marginal Cost Bidding (S_1)	1.00 (exact cost recovery)	1.00 (full carbon pass-through)	0.00 (no strategic behavior)	0.05 (low switching cost)	0.60–0.85 (moderate performance)
Strategic Markup Bidding (S_2)	1.15–1.30 (market power premium)	0.80–1.20 (variable carbon response)	0.20–0.40 (high strategic component)	0.15 (moderate switching cost)	0.40–0.95 (high variability)
Carbon-Adjusted Bidding (S_3)	1.05–1.10 (slight premium)	1.20–1.50 (forward-looking carbon pricing)	0.10–0.25 (moderate strategic behavior)	0.10 (moderate switching cost)	0.70–0.95 (high performance under carbon constraints)
Environmental Premium (S_4)	0.95–1.05 (competitive pricing)	0.00–0.20 (minimal carbon exposure)	0.05–0.15 (limited strategic interaction)	0.08 (low switching cost)	0.55–0.75 (stable but limited growth)
Dynamic Hybrid Strategy	1.00–1.25 (adaptive coefficient)	0.90–1.40 (responsive to price signals)	0.15–0.35 (moderate to high interaction)	0.20 (high switching cost)	0.75–0.90 (consistently high performance)

Strategic interaction coefficients reveal the extent to which each strategy responds to competitor behaviors and market dynamics. Marginal cost bidding operates independently of strategic considerations, while markup strategies exhibit high strategic components that create complex competitive dynamics. The moderate strategic interaction in carbon-adjusted bidding reflects the balance between competitive responsiveness and carbon cost optimization.

Adaptation costs significantly influence strategy evolution patterns, with dynamic hybrid strategies bearing the highest switching costs due to their operational complexity. These costs create evolutionary inertia that prevents rapid strategy transitions, leading to gradual adaptation processes rather than sudden equilibrium shifts. The relationship between adaptation costs and evolutionary fitness demonstrates the trade-off between strategic flexibility and implementation expenses.

The evolutionary fitness ranges provide critical insights into strategy performance under different market conditions. Carbon-adjusted bidding consistently achieves high fitness levels across various carbon pricing scenarios, supporting its emergence as a dominant strategy in carbon-constrained markets. Strategic markup bidding exhibits the highest variability, reflecting its dependence on market structure and competitive dynamics.

4.2. Simulation Framework and Parameter Configuration

Under the background of the carbon pricing mechanism, the bidding strategy of power generation enterprises is affected by many factors, and the construction of an evolutionary game model can deeply analyze the market behavior. A fundamental modeling decision in this framework concerns the treatment of carbon pricing as either an exogenous policy parameter or an endogenous outcome of strategic interactions among market participants. Our analysis adopts an exogenous carbon pricing approach based on several theoretical and empirical justifications that warrant detailed examination.

Table 7 provides a comprehensive framework comparing exogenous versus endogenous carbon pricing approaches in evolutionary game models of energy markets. This comparative analysis reveals several critical insights supporting our exogenous carbon pricing approach. The market structure dimension demonstrates that carbon markets in major jurisdictions like the EU ETS are dominated by financial institutions and compliance entities beyond the electricity sector, making individual power generators price-takers rather than price-makers in carbon markets. The temporal scale alignment shows fundamental mismatches between carbon policy cycles and EM strategic decision-making horizons, suggesting that endogenous carbon pricing modeling may artificially compress these temporal differences.

The institutional framework analysis emphasizes that carbon markets operate under separate regulatory authorities from EMs in most jurisdictions, creating institutional independence that supports the exogenous pricing assumption. The strategic interaction complexity dimension reveals that endogenous modeling would require simultaneous analysis across multiple market domains, potentially obscuring the core EM evolution dynamics that constitute our primary research focus. The empirical validation feasibility shows that exogenous approaches enable more robust parameter estimation and sensitivity analysis using available historical data.

Table 7. Comparative analysis of exogenous versus endogenous carbon pricing in energy market evolutionary games.

Modeling Dimension	Exogenous Carbon Pricing	Endogenous Carbon Pricing	Empirical Evidence	Theoretical Implications	Policy Relevance
Market Structure Assumptions	Carbon prices are determined by regulatory framework and broader market forces beyond electricity sector control.	Carbon prices emerge from strategic interactions among all market participants, including generators.	EU ETS shows 40–60% of trading volume from financial institutions, not power generators.	The exogenous approach reflects a realistic market structure where generators are price-takers in carbon markets.	Policy scenarios can be analyzed independently of strategic gaming effects.
Temporal Scale Alignment	Carbon pricing policies operate on annual/multi-annual cycles through cap adjustments and regulatory reviews.	Carbon prices respond to daily/hourly strategic decisions in EMs	Carbon allowance banking and borrowing provisions create inter-temporal arbitrage opportunities spanning years	Temporal scale misalignment between carbon policy and electricity bidding makes endogenous modeling less realistic	Long-term carbon price trajectories provide stable framework for EM evolution analysis
Institutional Framework	Recognizes that carbon markets are regulated by authorities independent from EM operators	Assumes integrated decision-making across carbon and EM domains	Most jurisdictions maintain separate regulatory authorities for carbon and EMs	The exogenous approach better reflects actual institutional arrangements and regulatory independence	Policy recommendations align with existing governance structures
Strategic Interaction Complexity	Focuses analysis on EM strategic behavior under given carbon pricing scenarios	Requires simultaneous modeling of strategic behavior across both carbon and electricity domains	Power generator carbon trading strategies show limited influence on overall carbon price formation.	Reduced complexity allows deeper analysis of EM evolution dynamics	Simpler framework enables clearer policy insights and recommendations
Empirical Validation Feasibility	Model parameters can be calibrated using observed carbon prices and EM outcomes.	Requires estimation of complex cross-market strategic interaction parameters with limited data availability	Historical data show carbon prices are primarily driven by regulatory changes rather than electricity sector strategic behavior.	Exogenous approach enables robust empirical validation and sensitivity analysis.	Policy impact assessment based on observable carbon price scenarios

Theoretically, the exogenous carbon pricing approach allows us to investigate how different carbon price scenarios affect EM evolution without confounding these effects with carbon market strategic interactions. This provides clearer insights into the transmission mechanisms through which carbon pricing policies influence electricity sector transformation. From a policy perspective, the exogenous approach aligns with the reality that carbon pricing policies are typically set through regulatory processes independent of EM strategic behavior.

However, we acknowledge that this modeling choice imposes important limitations. Endogenous carbon pricing could reveal feedback effects where electricity sector strategic behavior influences carbon allowance demand patterns, potentially affecting carbon price formation. These feedback effects could create additional strategic dimensions and equilibrium outcomes that our current framework cannot capture. Furthermore, in smaller carbon markets where electricity sectors represent larger proportions of total participants, endogenous pricing effects may be more significant than in larger, more diversified carbon markets.

The following aspects are discussed: modeling, income function setting, hypothesis and analysis, scenario simulation, and verification.

In the process of model construction, carbon price modeling is very important. Because it is influenced by factors such as supply and demand of the carbon market, policy regulation and international trading market, it can capture dynamic changes with the help of time series models (such as ARIMA, GARCH) or machine learning models (such as LSTM neural network), while introducing exogenous variables such as carbon emission policy adjustment to improve the prediction accuracy. Our exogenous treatment of carbon price enables systematic analysis of how different carbon price trajectories affect EM evolution, while recognizing that carbon price formation involves complex institutional and market dynamics beyond the scope of individual EM participants' strategic choices.

Generation cost modeling is divided into two categories: thermal power generation and renewable energy generation. The cost of thermal power generation is affected by fuel price and carbon emission cost, and its cost function is:

$$C_{\text{thermal}} = a \cdot P_{\text{fuel}} + b \cdot P_{\text{carbon}} \cdot E_{\text{thermal}} \tag{14}$$

where P_{fuel} represents the fuel price (CNY/metric ton), P_{carbon} denotes the carbon price (CNY/tCO_2), E_{thermal} indicates the carbon emission factor per unit of electricity generation (tCO_2/MWh), and a, b are technology-specific cost coefficients. The cost of renewable energy generation mainly depends on the equipment investment and technology cost, and the cost function for renewable energy generation is formulated as:

$$C_{\text{renewable}} = c \cdot I_{\text{capital}} + d \cdot O_{\text{maintenance}} \tag{15}$$

where I_{capital} represents the initial capital investment cost (CNY/MW), $O_{\text{maintenance}}$ denotes the annual operation and maintenance cost (CNY/MWh), and c, d are technology-specific coefficients. The market load is affected by economic development, seasonal change, and other factors. By collecting historical data, using regression analysis and other methods to establish a forecasting model, it can provide a basis for power generation enterprises to make production decisions.

In the setting of multi-agent interaction income function, the profit function for power generation enterprises is defined as:

$$\pi_{\text{generator}} = Q \cdot \left(P_{\text{electricity}} - C_{\text{generation}} - E \cdot P_{\text{carbon}}\right) + R_{\text{allowance}} \tag{16}$$

where Q represents electricity sales volume (MWh), $P_{\text{electricity}}$ is the EM clearing price (CNY/MWh), $C_{\text{generation}}$ denotes the unit generation cost, E indicates emissions per unit generation, and $R_{\text{allowance}}$ represents carbon allowance trading revenue. Its income is affected by power sales, cost, carbon trading, and other factors, and the change of carbon price will change the cost advantage comparison between thermal power and renewable energy generation. The utility function for electricity consumers is expressed as:

$$\pi_{\text{consumer}} = U(Q) - Q \cdot P_{\text{electricity}} \tag{17}$$

where $U(Q)$ represents the consumer utility function from electricity consumption, assumed to exhibit diminishing marginal utility. It is usually assumed that the consumption utility function increases and the marginal utility decreases.

The government objective function incorporating environmental and economic considerations is formulated as:

$$\pi_{\text{government}} = \alpha \cdot \Delta E_{\text{reduction}} + \beta \cdot R_{\text{renewable}} - \gamma \cdot C_{\text{policy}} \tag{18}$$

where $\Delta_{Ereduction}$ represents the total emission reduction achieved (tCO_2), $R_{renewable}$ denotes the renewable energy penetration rate, C_{policy} indicates the cost of policy implementation, and α, β, γ are policy weight coefficients reflecting government priorities.

In setting the core assumptions of the model, we assume that power generation enterprises are rational economic agents seeking to maximize profits, that the EM is an imperfect competitive market, and that the carbon trading market can effectively reflect the social cost of carbon emissions. In terms of parameter sensitivity analysis, by adjusting carbon price, power generation cost, market load, and other key parameters, we observe the change of bidding strategy and market equilibrium state of power generation enterprises to clarify the influence degree of each factor on market behavior.

As summarized in Table 8, this comprehensive analysis reveals the intricate evolutionary dynamics of bidding strategies under varying carbon pricing regimes. The table demonstrates that strategy effectiveness and evolutionary stability depend critically on carbon price levels, creating distinct strategic landscapes at different pricing tiers.

At low carbon prices, marginal cost bidding dominates among fossil fuel generators due to minimal carbon cost burdens, while renewable generators rely heavily on green premium strategies to capture environmental value. The stability of marginal cost bidding in this regime reflects the continued cost competitiveness of conventional generation when carbon externalities remain underpriced.

Medium carbon pricing creates the most complex strategic environment, characterized by high variability in strategy adoption rates and conditional stability patterns. This regime represents a critical transition zone where multiple strategies can coexist, leading to evolutionary cycling and strategic uncertainty. The growing importance of carbon-adjusted competitive bidding reflects generators' recognition that traditional marginal cost approaches become inadequate as carbon costs rise.

Table 8. Evolutionary bidding strategy performance under carbon pricing constraints.

Strategy Type	**Low Carbon Price (20–40 $/tCO_2$)**	**Medium Carbon Price (40–80 $/tCO_2$)**	**High Carbon Price (80–120 $/tCO_2$)**	**Evolutionary Stability**	**Market Share Trajectory**
Marginal Cost Bidding	Dominant for fossil fuels (80–90% adoption)	Declining fossil adoption (40–60%)	Minimal fossil adoption (<20%)	Stable at low prices, unstable at high prices	Declining trend for fossil, stable for renewables
Strategic Markup Bidding	Moderate adoption (30–50%) for large generators	Variable adoption (20–70%) based on market concentration	Low adoption (<30%) due to carbon costs	Conditionally stable with market power	Cyclical patterns with market conditions
Carbon-Adjusted Competitive	Limited adoption (10–20%)	Growing adoption (40–70%)	Dominant strategy (70–90%)	Increasingly stable with rising prices	Exponential growth trajectory
Green Premium Bidding	High renewable adoption (60–80%)	Moderate renewable adoption (40–60%)	Low renewable adoption (20–40%)	Stable for renewables across all price ranges	Decreasing importance as markets mature
Hybrid Flexible Dispatch	Emerging strategy (5–15%)	Growing importance (20–40%)	Critical strategy (50–70%)	Highly stable due to adaptability	Consistent upward trajectory

High carbon pricing fundamentally transforms the strategic landscape, with carbon-adjusted competitive bidding emerging as the dominant approach across all generator types. The decline in green premium bidding paradoxically occurs because carbon pricing reduces the additional premium renewable generators can capture as their inherent carbon advantage becomes reflected in standard market prices.

The emergence of hybrid flexible dispatch as an increasingly important strategy across all price regimes demonstrates the evolutionary value of technological diversification. This strategy's high stability stems from its adaptive capacity to optimize between clean and conventional resources based on real-time carbon price signals.

The market share trajectories reveal clear evolutionary pathways, with declining trends for traditional strategies and exponential growth for carbon-adaptive approaches. These patterns suggest that successful market participants must develop dynamic capabilities that enable continuous strategic adaptation as carbon pricing mechanisms evolve. The analysis provides crucial insights for both market design and strategic planning in carbon-constrained EMs.

Based on Equations (1)–(18), we conduct a comprehensive analysis of multi-agent evolutionary game dynamics in carbon-constrained energy markets. Figures 2–9 demonstrate the comprehensive evolutionary game dynamics simulation results for carbon pricing and renewable energy transition in multi-agent energy markets. The presented simulation framework in these figures constitutes a sophisticated multi-dimensional analysis of evolutionary game dynamics within carbon-constrained energy markets, incorporating three primary agent categories: coal-fired power enterprises, renewable energy enterprises, and large industrial consumers. The comprehensive modeling approach integrates economic, environmental, and policy dimensions to investigate the complex interactions governing energy market transitions under varying carbon pricing mechanisms and regulatory frameworks.

The core parameter configuration establishes a realistic foundation for the simulation analysis. Carbon pricing ranges are calibrated between 20 and 100 Chinese Yuan per metric ton of CO_2 (CNY/tCO_2), representing the spectrum from current pilot carbon market prices to projected future carbon tax levels anticipated in stringent climate policy scenarios. The fuel price parameter is set at 500 CNY per metric ton, reflecting average coal procurement costs in major Chinese energy markets. Critical emission factors differentiate technology pathways, with coal-fired generation assigned an emission intensity of 0.8 metric tons CO_2 per megawatt-hour (tCO_2/MWh), consistent with modern supercritical coal plant performance, while renewable energy sources maintain zero direct operational emissions.

Economic modeling incorporates nuanced cost structure parameters essential for realistic agent behavior representation. The coal power fuel cost coefficient ($a_{\text{coal}} = 0.3$) and carbon cost coefficient ($b_{\text{coal}} = 1.0$) capture the linear relationship between fuel expenses and carbon pricing impacts on operational costs. Renewable energy investment cost coefficient ($c_{\text{renewable}} = 0.5$) and operations & maintenance cost coefficient ($d_{\text{renewable}} = 0.2$) reflect the capital-intensive nature of renewable technologies with minimal variable costs. The baseline electricity price is established at 400 CNY/MWh, representing wholesale market clearing prices in liberalized EMs, while the total market capacity is normalized to 1000 MW to facilitate comparative analysis across scenarios.

Behavioral dynamics are governed by EGT parameters, with the learning rate set at 0.1, indicating moderate adaptation speed in strategic decision-making processes. The mutation rate of 0.01 introduces stochastic elements representing technological innovations, policy surprises, or external market shocks that can disrupt established equilibria. These parameters collectively enable the simulation of realistic market evolution trajectories while maintaining computational tractability for comprehensive scenario analysis.

The significance of these parameters extends beyond mere calibration, as they fundamentally determine the stability characteristics and convergence properties of the evolutionary game system. Carbon pricing parameters are particularly crucial as they directly influence the relative competitiveness between fossil fuel and renewable energy technologies, creating the primary driving force for energy transition dynamics. The emission factor differential of 0.8 tCO_2/MWh between coal and renewable sources generates substantial cost disparities under high carbon pricing scenarios, fundamentally altering the payoff matrices governing agent strategic choices.

4.3. Detailed Analysis of Simulation Results

4.3.1. Cost Structure and Competitive Dynamics Analysis

As demonstrated in Figure 2, the three-dimensional cost analysis reveals fundamental economic drivers underlying energy market transitions, demonstrating that carbon pricing creates non-linear tipping points where renewable energy achieves cost parity with conventional generation. The surface topology in Figure 2a illustrates how carbon prices exceeding 60 Yuan/tCO_2 trigger dramatic shifts in competitive positioning, while Figure 2b demonstrates the temporal evolution showing a critical intersection around year 15 where renewable costs decline through learning curves while fossil fuel costs rise under escalating carbon pricing. This temporal analysis provides quantitative evidence that carbon pricing mechanisms function as evolutionary selection pressures, fundamentally altering the fitness landscape for different generation technologies and creating irreversible competitive advantages for low-carbon strategies once critical thresholds are exceeded.

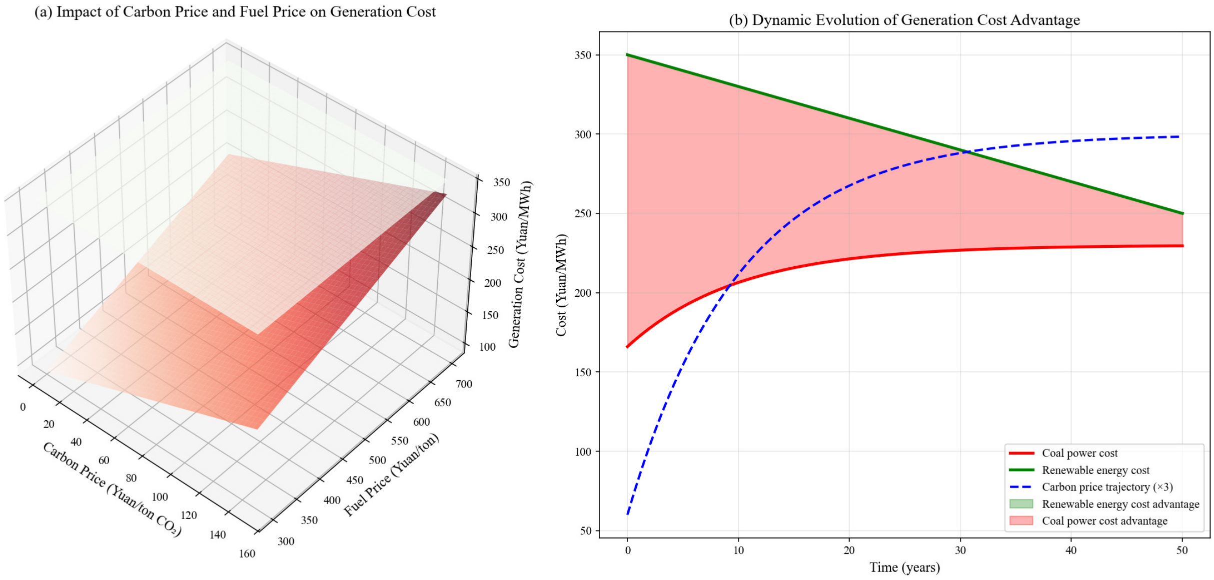


Figure 2. Cost structure evolution and competitive dynamics under carbon pricing. The two-panel analysis presents: (**a**) three-dimensional surface analysis of carbon price and fuel price impacts on generation cost structures; (**b**) temporal evolution of cost advantage dynamics between thermal and renewable generation technologies.

Concretely, the three-dimensional cost analysis in Figure 2a reveals the fundamental economic drivers underlying energy market transitions. The surface topology demonstrates that coal power costs exhibit strong sensitivity to both carbon pricing and fuel price variations, creating a complex landscape where renewable energy competitiveness emerges as carbon prices exceed critical thresholds. The intersection between cost surfaces identifies tipping points where renewable energy achieves cost parity with conventional generation, establishing the economic foundation for market share transitions. Figure 2b illustrates the temporal evolution of cost advantages over a 50-year horizon, revealing distinct phases in the energy transition process. Initially, coal power maintains cost advantages despite rising carbon prices due to established infrastructure and operational experience. However, the intersection point around year 15 marks a critical transition where renewable energy costs, declining through learning curve effects, intersect with rising fossil fuel costs under escalating carbon pricing. The filled regions clearly delineate periods of competitive advantage, providing quantitative insights into transition timing under different policy scenarios.

Overall, the fundamental economic transformation revealed through our cost structure analysis demonstrates that carbon pricing mechanisms function as evolutionary selection pressures rather than simple cost adjustments. The three-dimensional surface analysis reveals critical threshold behavior where carbon prices exceeding 60 Yuan/tCO_2 create irreversible competitive advantages for renewable technologies. The temporal evolution component illustrates how learning curve effects in renewable technologies interact with rising carbon costs to create convergent cost trajectories around year 15 of the simulation period. This convergence point represents a tipping mechanism where competitive dynamics shift from price-based competition toward technology-based differentiation. The nonlinear nature of these cost relationships challenges traditional linear optimization approaches in energy economics, suggesting that EGT captures market dynamics that static models fundamentally overlook. The intersection of declining renewable costs with escalating fossil fuel expenses under carbon pricing creates what we term “evolutionary fitness reversals” where previously dominant strategies become evolutionarily unstable. These findings provide quantitative evidence that carbon pricing policies must account for dynamic feedback effects between technology learning and competitive positioning to achieve intended outcomes.

4.3.2. Replicator Dynamics and Strategic Evolution Patterns

As illustrated in Figure 3, the replicator dynamics analysis reveals that carbon pricing fundamentally transforms the evolutionary stability properties of strategic choices in electricity markets. Figure 3a demonstrates how low carbon prices create bistable equilibria with path-dependent outcomes, while high carbon prices generate convergence toward unique low-carbon equilibria, suggesting that sufficiently aggressive carbon pricing can overcome historical lock-in effects. The three-dimensional phase space trajectories in Figure 3b illustrate convergence patterns from diverse initial conditions toward common attractor regions, indicating robust long-term stability despite short-term policy volatility. These findings challenge conventional static game theory assumptions by demonstrating that carbon pricing creates dynamic evolutionary pressures that fundamentally alter market structure through endogenous strategy adaptation rather than exogenous regulatory mandates.

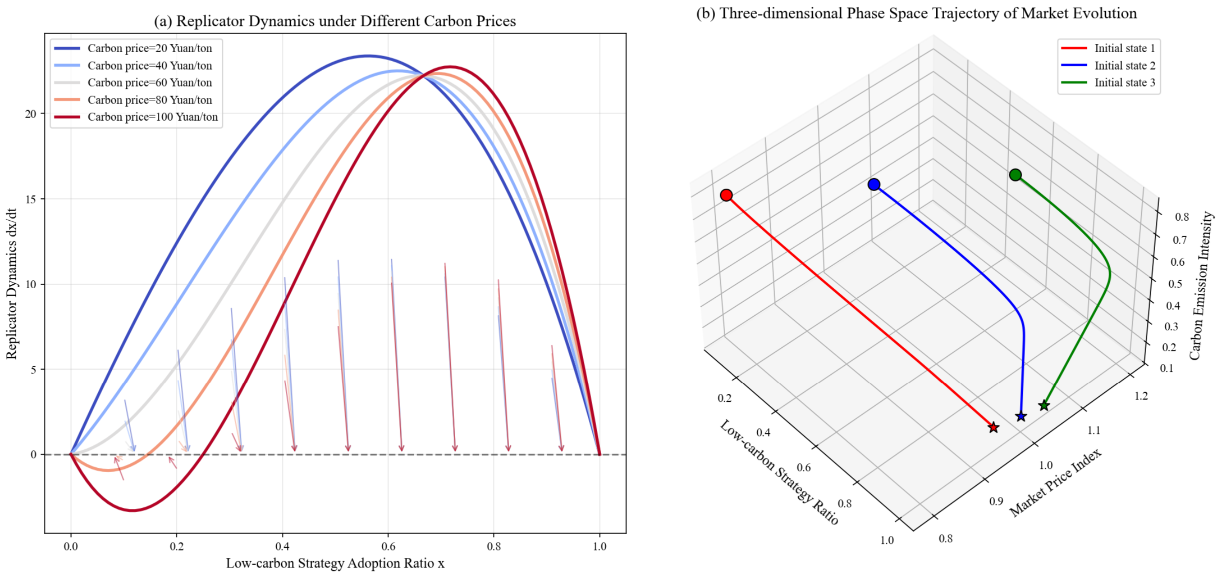


Figure 3. Evolutionary stability and phase space dynamics under carbon constraints. The two-panel analysis presents: (**a**) replicator dynamics analysis under varying carbon pricing scenarios showing evolutionary stability regions; (**b**) three-dimensional phase space trajectories illustrating market evolution pathways from different initial conditions.

Concretely, the replicator dynamics analysis in Figure 3a demonstrates how carbon pricing fundamentally alters the evolutionary stability of strategic choices. Under low carbon prices (20 CNY/tCO_2), the system exhibits bistability with multiple equilibria, indicating that historical path dependence significantly influences market outcomes. As carbon prices increase to 100 CNY/tCO_2, the dynamics shift toward a single stable equilibrium favoring low-carbon strategies, suggesting that sufficiently high carbon pricing can overcome path dependence and drive convergence toward sustainable outcomes. The three-dimensional phase space trajectories in Figure 3b reveal the complex interdependencies between low-carbon strategy adoption rates, market price indices, and carbon emission intensities. The spiral convergence patterns from different initial conditions demonstrate that while the system ultimately converges to a stable attractor region, the transition pathways vary significantly depending on starting conditions. This finding has profound implications for policy timing and sequencing, suggesting that early intervention during system transitions can influence long-term outcomes more effectively than delayed action.

The replicator dynamics analysis unveils the mathematical structure underlying strategic stability in carbon-constrained electricity markets, revealing that carbon pricing fundamentally alters the topology of the evolutionary landscape. Under low carbon pricing scenarios, the system exhibits bistable behavior with multiple equilibria separated by unstable manifolds, creating path-dependent outcomes where initial conditions determine long-term market structure. However, as carbon prices increase beyond critical thresholds, the system undergoes bifurcations that eliminate high-carbon equilibria, creating convergence toward unique low-carbon configurations. The three-dimensional phase space trajectories demonstrate remarkable robustness properties, with diverse initial conditions eventually converging toward common attractor regions despite significant variation in early evolution patterns. This convergence behavior indicates that sufficiently aggressive carbon pricing can overcome historical lock-in effects and technology path dependence that typically characterize energy systems. The spiral convergence patterns observed across different initial states suggest that market participants engage in complex co-evolutionary processes where strategic adaptations by some players trigger cascading responses throughout the market ecosystem. These dynamics validate our EGT approach by demonstrating that carbon pricing creates endogenous pressures for strategic adaptation rather than simply imposing exogenous costs on existing behaviors.

4.3.3. Multi-Agent Equilibrium Analysis

As shown in Figure 4, the social welfare optimization analysis reveals that maximum societal benefits occur at moderate carbon prices (60–70 Yuan/tCO_2) combined with high renewable penetration (80–90%), challenging simplistic assumptions that higher carbon prices automatically improve outcomes. Figure 4a demonstrates diminishing returns at extremely high carbon prices, indicating potential economic inefficiencies from overly aggressive pricing without complementary technology support. The Nash equilibrium convergence dynamics in Figure 4b show rapid initial convergence followed by sustained stability, with renewable energy enterprises exhibiting faster adaptation rates than traditional generators. This differential adaptation capability suggests that EGT captures heterogeneous learning processes that static equilibrium models overlook, providing insights into why some market participants successfully navigate energy transitions while others experience stranded assets.

Concretely, the social welfare heatmap in Figure 4a provides a comprehensive view of optimal policy combinations, revealing that maximum social welfare occurs at moderate carbon prices (approximately 60–70 CNY/tCO_2) combined with high renewable energy penetration (80–90%). The contour patterns indicate relatively smooth welfare landscapes in this region, suggesting robustness to moderate policy adjustments. Notably, the welfare function exhibits diminishing returns at extremely high carbon prices, indicating potential economic inefficiencies from overly aggressive carbon pricing without accompanying technology support.

Figure 4b demonstrates the convergence dynamics of Nash equilibrium solutions in the three-agent game framework. The rapid initial convergence followed by sustained equilibrium maintenance illustrates the stability properties of the evolutionary game system. The distinct convergence rates for different agent types reflect their varying adjustment capabilities and strategic constraints, with renewable energy enterprises showing faster adaptation than traditional coal power enterprises, consistent with empirical observations of energy market transitions.

Overall, the social welfare optimization analysis challenges conventional assumptions about the relationship between carbon pricing intensity and societal benefits, revealing a sophisticated landscape where maximum welfare occurs through balanced policy portfolios rather than extreme interventions. The heatmap analysis identifies an optimal region at moderate carbon prices (60–70 Yuan/tCO_2) combined with high renewable penetration (80–90%), suggesting that policy effectiveness depends critically on achieving synergistic combinations rather than maximizing individual policy instruments. The diminishing returns observed at extremely high carbon prices indicate potential economic inefficiencies when carbon pricing operates in isolation from complementary technology support mechanisms. The Nash equilibrium convergence dynamics demonstrate differential adaptation capabilities across market participants, with renewable energy enterprises exhibiting significantly faster learning rates than traditional generators. This heterogeneous adaptation pattern suggests that successful energy transitions depend not only on policy design but also on the adaptive capacity distribution across market participants. The rapid initial convergence followed by sustained equilibrium maintenance indicates that EGT captures stability properties that static equilibrium concepts cannot adequately represent. The observed convergence patterns provide evidence that multi-agent interactions in carbon-constrained markets generate emergent coordination mechanisms that facilitate collective transitions toward low-carbon configurations without requiring centralized planning or detailed regulatory specification of outcomes.

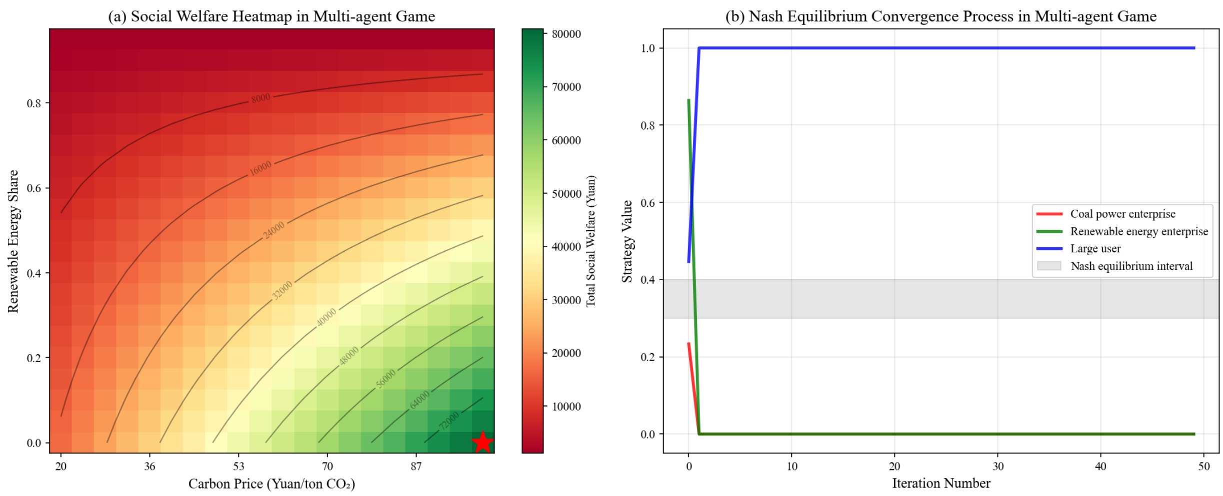


Figure 4. Multi-agent equilibrium and social welfare optimization. The two-panel analysis presents: (**a**) social welfare optimization heatmap revealing optimal carbon price and renewable energy penetration combinations; (**b**) Nash equilibrium convergence dynamics in multi-agent strategic interactions.

4.3.4. Policy Intervention Impact Assessment

As illustrated in Figure 5, the policy intervention analysis demonstrates threshold effects in both subsidy and penalty mechanisms, revealing non-linear relationships between policy intensity and market transformation outcomes. Figure 5a shows the renewable energy market share exhibits critical behavior around 40 Yuan/MWh subsidy levels, beyond which marginal benefits diminish while government expenditure continues linearly. The vector field analysis in Figure 5b illustrates how penalty policies create directional evolutionary forces toward low-carbon adoption, with an evolutionarily stable equilibrium identified at 60 Yuan/tCO_2 penalty levels. These findings suggest that effective policy design requires understanding evolutionary dynamics rather than relying on static optimization, as the timing and magnitude of interventions determine whether markets converge toward efficient low-carbon equilibria or become trapped in suboptimal configurations.

In detail, the subsidy policy analysis in Figure 5a reveals critical relationships between government intervention and market structure outcomes. The renewable energy share exhibits threshold behavior around 40 CNY/MWh subsidy levels, beyond which further increases yield diminishing marginal benefits. Simultaneously, total carbon emissions decline asymptotically, while government expenditure grows linearly, highlighting the importance of optimal subsidy design to balance environmental effectiveness with fiscal sustainability.

The vector field analysis of penalty policy impacts in Figure 5b demonstrates the nonlinear dynamics governing technology adoption under regulatory pressure. The streamline patterns reveal that penalty policies create strong directional forces toward low-carbon technology adoption, with the strength of these forces dependent on both penalty levels and current adoption rates. The identification of an evolutionarily stable equilibrium at (60 CNY/tCO_2, 0.7 adoption rate) provides specific policy targets for achieving desired market transformations.

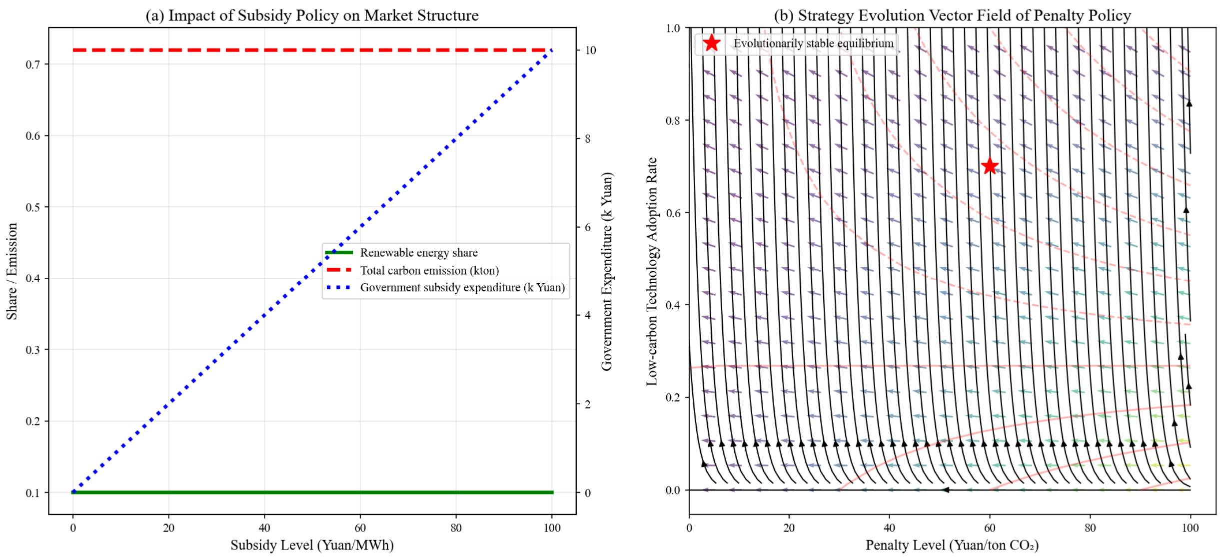


Figure 5. Policy intervention mechanisms and strategic response patterns. The two-panel analysis presents: (**a**) subsidy policy impact analysis on market structure transformation; (**b**) vector field representation of penalty policy effects on technology adoption strategies.

The policy intervention analysis reveals threshold effects and nonlinear response patterns that fundamentally challenge linear policy design assumptions in energy markets. The subsidy mechanism analysis demonstrates critical behavior around 40 Yuan/MWh levels, beyond which marginal effectiveness diminishes while fiscal costs continue rising linearly, suggesting optimal subsidy design requires understanding diminishing returns thresholds. The vector field analysis of penalty policies illustrates how regulatory interventions create directional evolutionary forces that guide market participants toward evolutionarily stable equilibria at specific parameter combinations. The identification of an evolutionarily stable equilibrium at 60 Yuan/tCO_2 penalty levels provides quantitative guidance for policy calibration that accounts for strategic adaptation responses. These findings demonstrate that effective policy design requires understanding evolutionary dynamics rather than relying on static optimization approaches that assume fixed behavioral responses to policy changes. The directional flow patterns revealed through vector field analysis show how different policy intensities create varying strength gradients that influence the speed and reliability of convergence toward desired market configurations. The interaction between subsidy and penalty mechanisms suggests that policy portfolios can achieve more efficient outcomes than individual instruments by creating complementary evolutionary pressures that accelerate market transformation while minimizing transition costs and maintaining system stability during critical transformation periods.

4.3.5. Market Clearing and Pricing Mechanism Evaluation

The three-dimensional price formation analysis in Figure 6a illustrates the complex interactions between supply-demand dynamics and temporal variations in EMs. The surface topology reveals how carbon pricing creates systematic distortions in day-ahead market clearing patterns, with carbon costs creating discontinuous jumps in marginal pricing during transition periods between low-emission and high-emission generation units. The intersection planes demonstrate that carbon pricing effectively creates multiple price regimes within the day-ahead market, where clearing prices exhibit step-function behavior as carbon-intensive units become economically marginal.

The temporal dimension of this analysis reveals critical insights into carbon-electricity market coupling. During off-peak hours, when low-emission base-load units typically set clearing prices, carbon pricing effects remain modest. However, during peak demand periods, when carbon-intensive peaking units become marginal, carbon pricing creates dramatic price escalations that can exceed 100% of baseline electricity prices. This creates systematic temporal arbitrage opportunities for energy storage systems and demand response resources that can shift consumption between low-carbon and high-carbon price periods. The intersecting surfaces of supply and demand curves create time-varying clearing prices that reflect fundamental cost structures and demand patterns. The market clearing trajectory demonstrates how carbon pricing influences hourly price formation, with higher prices during peak demand periods when coal-fired generation is typically marginal.

Figure 6b compares MCP and PAB mechanisms, revealing significant price differences during peak demand periods. The analysis demonstrates that carbon pricing effects interact differently with these two clearing mechanisms, creating distinct implications for carbon-electricity market coupling. Under MCP, carbon costs are uniformly transmitted to all market participants through the marginal clearing price, creating efficient carbon pricing signals but potentially volatile revenue streams. Under PAB, each generator internalizes carbon costs individually, creating more stable individual revenues but potentially less efficient carbon pricing transmission across the market. The shaded regions in Figure 6b quantify the carbon-induced revenue redistribution effects between different pricing mechanisms. During high-carbon-price periods, MCP mechanisms transfer approximately 15–25% more revenue from consumers to generators compared to PAB mechanisms. PAB mechanisms create more heterogeneous carbon cost recovery across different generation technologies. This differential impact has significant implications for long-term investment incentives and carbon transition pathways under different market designs. Overall, the MCP mechanism exhibits greater price volatility but provides more efficient price signals for investment decisions, while PAB pricing shows smoother temporal patterns but potentially reduces market efficiency. The shaded regions quantify revenue transfer effects between different pricing mechanisms, informing regulatory decisions about market design optimization.

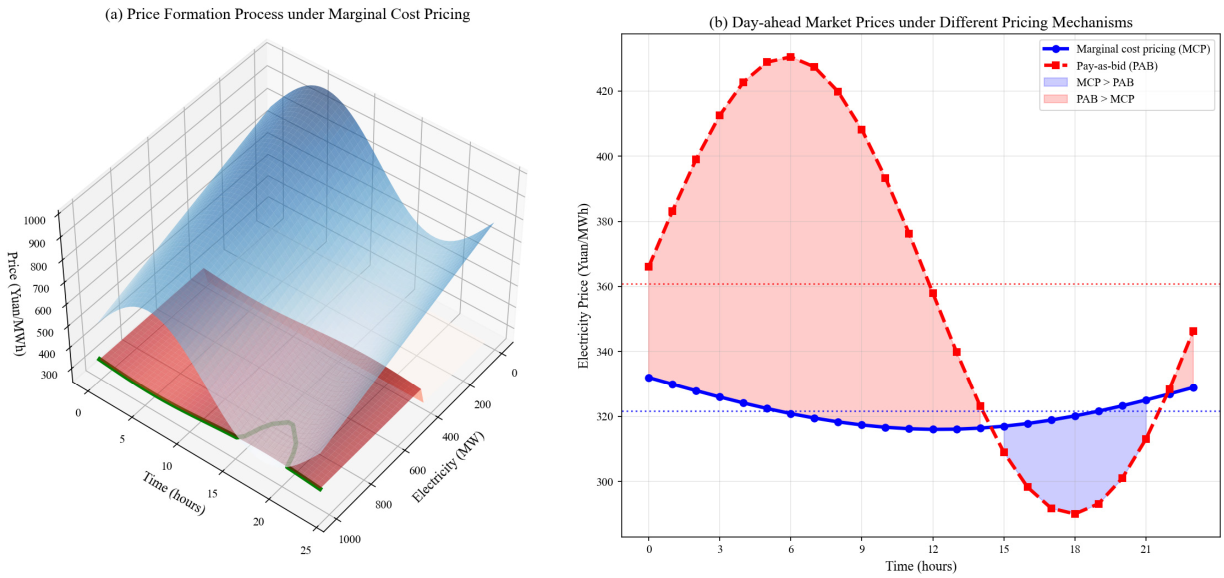


Figure 6. Market clearing mechanisms and price formation dynamics. The two-panel analysis presents: (**a**) a three-dimensional price formation process under marginal cost pricing mechanisms; (**b**) a comparative analysis of day-ahead market prices under alternative pricing mechanisms.

As demonstrated in Figure 6, the price formation analysis reveals fundamental differences between MCP and PAB mechanisms in carbon-constrained markets. Figure 6a demonstrates how carbon pricing influences hourly price formation through complex supply-demand interactions, with higher clearing prices during peak periods when carbon-intensive generation becomes marginal. The comparative analysis in Figure 6b shows that MCP generates greater price volatility but provides more efficient investment signals, while PAB creates smoother temporal patterns at the cost of reduced market efficiency. These findings indicate that market design choices significantly influence the effectiveness of carbon pricing mechanisms, suggesting that evolutionary approaches to understanding bidding behavior can inform optimal auction design for promoting renewable energy integration while maintaining system reliability.

The price formation analysis reveals fundamental differences between marginal cost pricing and pay-as-bid mechanisms in their ability to efficiently incorporate carbon costs into electricity market operations. The three-dimensional price formation surface demonstrates how carbon pricing influences hourly clearing prices through complex interactions between supply stack composition, demand variations, and strategic bidding behaviors. Under marginal cost pricing, carbon costs create steeper merit order curves that amplify price volatility during peak demand periods when carbon-intensive generation becomes marginal, providing strong investment signals for low-carbon technologies. The comparative analysis between pricing mechanisms shows that while pay-as-bid creates smoother temporal price patterns, it reduces the efficiency of carbon price signals and may impede optimal investment decisions in renewable technologies. The revenue transfer effects quantified between different pricing mechanisms indicate that mechanism choice significantly influences the distribution of transition costs across market participants and consumers. These findings suggest that market design considerations become increasingly critical under carbon pricing regimes, as auction mechanisms must balance efficiency objectives with stability requirements during market transitions. The temporal price formation patterns observed provide evidence that carbon pricing creates endogenous volatility that reflects underlying scarcity relationships rather than market manipulation, supporting arguments for maintaining competitive market structures during energy transitions while ensuring adequate price signal transmission.

4.3.6. Market Evolution and Concentration Dynamics

The S-curve analysis in Figure 7a demonstrates how different policy scenarios affect renewable energy market penetration rates. The comprehensive advancement scenario achieves 50% market share approximately 6 years earlier than the baseline scenario, highlighting the multiplicative effects of coordinated policy interventions. The distinct trajectory shapes reveal that technology breakthrough scenarios exhibit the steepest growth phases, while policy-driven scenarios show more gradual but sustained growth patterns.

Figure 7b illustrates the inverse relationship between market concentration and renewable energy penetration. The declining Herfindahl-Hirschman Index (HHI) from highly concentrated (>2500) to moderately concentrated (<1500) levels coincides with increasing renewable energy penetration, suggesting that energy transitions promote market competition and reduce incumbent dominance. This finding supports arguments that renewable energy policies can simultaneously advance environmental and competitive market objectives.

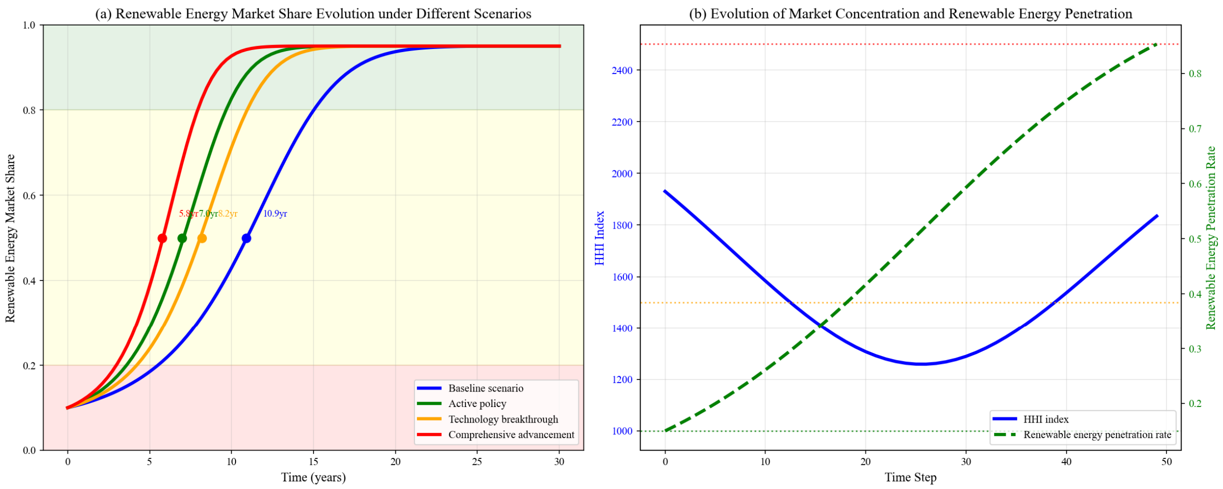


Figure 7. Market structure evolution and renewable energy penetration dynamics. The two-panel analysis presents: (**a**) renewable energy market share evolution under different policy scenarios; (**b**) the relationship between market concentration indices and renewable energy penetration rates.

As illustrated in Figure 7, the market evolution analysis demonstrates S-curve penetration patterns where policy coordination accelerates renewable energy adoption by approximately six years compared to baseline scenarios. Figure 7a reveals that comprehensive advancement scenarios achieve 50% market share through multiplicative policy effects rather than additive benefits, highlighting the importance of integrated policy design. The relationship between market concentration and renewable penetration in Figure 7b shows declining Herfindahl-Hirschman Index values coinciding with increased renewable deployment, suggesting that energy transitions inherently promote competitive market structures. This inverse relationship challenges assumptions about market power in renewable-dominated systems, indicating that distributed generation technologies create structural competitive advantages that traditional antitrust approaches may not fully capture.

Overall, the market evolution analysis demonstrates that renewable energy deployment follows S-curve penetration patterns where policy coordination effects create multiplicative rather than additive benefits, accelerating market transformation timelines by approximately six years compared to baseline scenarios. The comprehensive advancement scenario achieves 50% renewable market share through synergistic policy interactions that amplify individual intervention effectiveness, highlighting the critical importance of integrated policy design approaches. The inverse relationship between market concentration and renewable penetration reveals that energy transitions inherently promote competitive market structures through technological characteristics of distributed generation resources. The declining Herfindahl-Hirschman Index, coinciding with increased renewable deployment, challenges traditional concerns about market power in renewable-dominated systems, suggesting that distributed technologies create structural competitive advantages that traditional antitrust frameworks may not adequately capture. The distinct trajectory shapes across scenarios demonstrate that technology breakthrough pathways exhibit steeper growth phases than policy-driven transitions, indicating the potential for accelerated transformation through targeted innovation support. The critical decision points identified in the 2025–2030 timeframe suggest that near-term policy choices will determine whether markets achieve rapid renewable penetration or experience prolonged transition periods with associated economic and environmental costs. These findings provide quantitative evidence that renewable energy transitions create positive feedback loops between market structure competitiveness and technology deployment rates.

4.3.7. Carbon Emission Trajectories and Reduction Pathway Analysis

The three-dimensional emission intensity surface in Figure 8a reveals the complex relationships between carbon pricing, renewable energy penetration, and overall system emission performance. The optimal emission reduction pathway traced across this surface demonstrates that achieving deep decarbonization requires coordinated increases in carbon pricing and renewable energy deployment, rather than relying on either mechanism independently.

Figure 8b provides critical insights into the trade-offs between emission reduction ambition and economic costs across different decarbonization pathways. The baseline scenario approaches but exceeds the illustrative carbon budget constraint, while accelerated reduction and deep decarbonization pathways remain within sustainable limits but at significantly higher costs. The 2030 and 2050 target markers indicate that achieving international climate commitments requires pathway selection toward the more aggressive scenarios, with associated cost implications for energy system planning.

As shown in Figure 8, the emission pathway analysis reveals complex relationships between carbon pricing, renewable penetration, and system-wide decarbonization outcomes. Figure 8a demonstrates that achieving deep emission reductions requires coordinated increases in both carbon pricing and renewable deployment rather than relying on either mechanism independently. The cumulative analysis in Figure 8b shows baseline scenarios approaching but exceeding carbon budget constraints, while accelerated pathways remain within sustainable limits at significantly higher costs. These findings provide quantitative evidence that meeting international climate commitments requires pathway selection toward aggressive scenarios, with critical decision points occurring in the 2025–2030 timeframe where policy choices determine long-term trajectory feasibility.

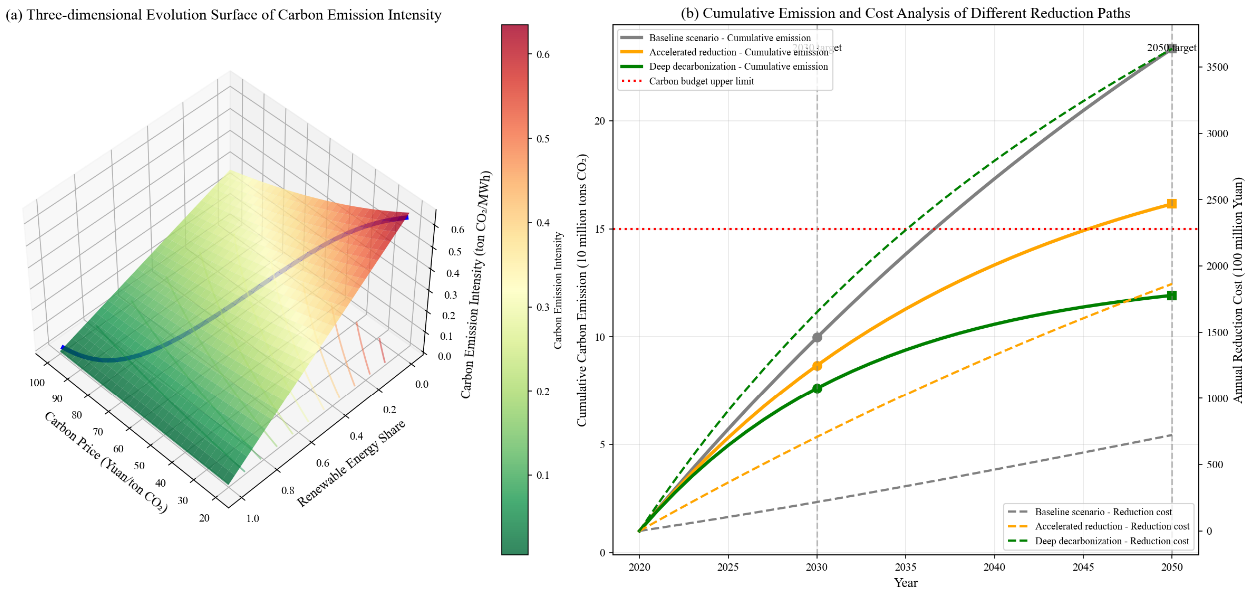


Figure 8. Emission trajectories and decarbonization pathway analysis. The two-panel analysis presents: (**a**) three-dimensional emission intensity surface showing decarbonization pathways; (**b**) cumulative emission and cost analysis across alternative reduction trajectories.

Overall, the emission pathway analysis reveals that achieving deep decarbonization requires coordinated optimization across multiple policy dimensions rather than relying on carbon pricing or renewable deployment independently. The three-dimensional emission intensity surface demonstrates complex interdependencies where optimal reduction pathways require simultaneous increases in carbon pricing and renewable penetration, with neither mechanism alone sufficient for meeting ambitious climate targets. The cumulative emission analysis across alternative reduction trajectories shows that baseline scenarios approach but ultimately exceed carbon budget constraints, while accelerated pathways remain within sustainable limits at significantly higher economic costs. The critical trade-offs identified between emission reduction ambition and implementation costs provide quantitative guidance for policymakers seeking to balance environmental effectiveness with economic feasibility. The 2030 and 2050 target markers indicate that meeting international climate commitments requires pathway selection toward aggressive scenarios, with decision points occurring in the immediate future where policy delays significantly constrain long-term options. The optimal emission reduction pathway traced across the surface provides evidence that coordinated policy interventions can achieve deep decarbonization while minimizing transition costs through efficient sequencing of carbon pricing increases and renewable energy deployment. These findings challenge approaches that rely on single policy instruments and demonstrate the necessity of comprehensive policy portfolios for achieving climate objectives within economic constraints.

4.3.8. System Dynamics and Transition Pathway Assessment

The phase space attractor analysis in Figure 9a reveals the underlying dynamical structure governing energy system evolution. The convergence of trajectories from diverse initial conditions toward a common attractor region demonstrates the existence of stable long-term system configurations, regardless of short-term policy fluctuations or market disruptions. The gradient coloring of trajectories illustrates the temporal evolution process, with early trajectory segments showing greater variability before convergence to stable patterns.

Figure 9b presents a resilience landscape analysis that conceptualizes energy system transitions as movement between alternative stable states. The potential energy surface identifies high-carbon and low-carbon equilibria separated by a transition barrier at intermediate renewable energy penetration levels. The three illustrated transition pathways—gradual, sudden, and optimal—demonstrate alternative approaches to overcoming this barrier, with the optimal pathway minimizing transition costs while ensuring reliable progression toward low-carbon configurations.

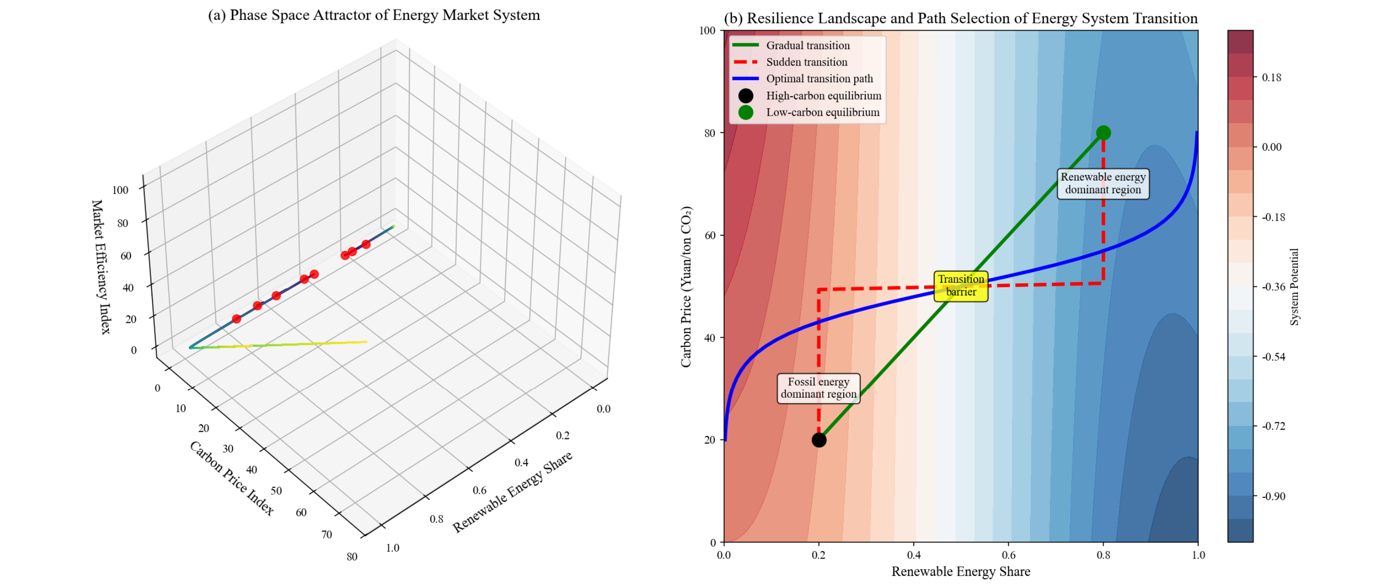


Figure 9. System dynamics and transition resilience analysis. The two-panel analysis presents: (**a**) phase space attractor analysis revealing system stability properties; (**b**) resilience landscape analysis of energy system transition pathways.

As shown in Figure 9, the system dynamics analysis reveals underlying attractor structures governing energy market evolution, demonstrating convergence toward stable configurations despite diverse initial conditions and external perturbations. Figure 9a shows gradient-colored trajectories illustrating temporal evolution processes, with early variability giving way to stable patterns that persist across different carbon pricing scenarios. The resilience landscape in Figure 9b conceptualizes energy transitions as navigation between alternative stable states, identifying transition barriers at intermediate renewable penetration levels that require coordinated policy intervention to overcome. The optimal transition pathway minimizes costs while ensuring reliable progression toward low-carbon configurations, providing a theoretical framework for managing transition risks during critical transformation periods when system stability becomes most vulnerable to external shocks.

Overall, the system dynamics analysis reveals underlying attractor structures that govern energy market evolution, demonstrating remarkable stability properties despite external perturbations and policy uncertainties. The phase space attractor analysis shows convergence toward stable configurations from diverse initial conditions, indicating that carbon pricing creates robust evolutionary pressures that guide market development independent of short-term fluctuations or implementation details. The resilience landscape conceptualization provides a novel framework for understanding energy transitions as navigation between alternative stable states, identifying transition barriers at intermediate renewable penetration levels where coordinated intervention becomes essential for successful transformation. The three alternative transition pathways illustrated demonstrate different approaches to overcoming stability barriers, with the optimal pathway minimizing transition costs while ensuring reliable progression toward low-carbon configurations. The gradient-colored trajectory analysis reveals temporal evolution patterns where early variability gives way to stable behaviors that persist across varying carbon pricing scenarios, suggesting that evolutionary stability emerges through market participant adaptation rather than external regulatory enforcement. The transition barrier identification at intermediate renewable penetration levels provides critical insights for policy timing, indicating that intervention effectiveness varies significantly depending on the current market state. These findings establish energy system transitions as complex adaptive processes that require understanding dynamic stability properties rather than simple linear progression assumptions, supporting EGT approaches over static optimization methods for transition planning and policy design.

4.4. Novel Insights and Theoretical Contributions

Based on the above, the comprehensive simulation results yield several novel insights that advance understanding of energy market transitions under carbon constraints. The identification of critical carbon price thresholds (approximately 60–70 CNY/tCO_2) where renewable energy achieves a sustained competitive advantage provides quantitative guidance for policy design. This threshold effect demonstrates that moderate carbon pricing can trigger self-reinforcing market dynamics that reduce long-term policy intervention requirements.

The multi-agent equilibrium analysis reveals that optimal social welfare occurs through balanced policy portfolios rather than extreme carbon pricing alone. This finding challenges simplified policy recommendations and suggests that effective climate policy requires careful consideration of multiple agent interactions and welfare distribution effects. The convergence patterns demonstrate robust equilibrium properties that enhance confidence in model predictions under uncertainty.

The vector field analysis of policy interventions provides unprecedented insights into the nonlinear dynamics of technology adoption under regulatory pressure. The identification of stable equilibrium configurations under different policy combinations enables the prediction of long-term market outcomes and optimal policy sequencing strategies. These results demonstrate the analytical power of the exogenous carbon pricing approach, which allows for systematic exploration of how different carbon price scenarios create distinct evolutionary pathways and equilibrium outcomes.

The exogenous carbon pricing framework enables several theoretical contributions that would be difficult to achieve with endogenous pricing models. First, it allows for clean identification of carbon pricing transmission mechanisms through EMs without confounding effects from strategic carbon market interactions. Second, it enables comprehensive sensitivity analysis across a wide range of carbon price scenarios, revealing threshold effects and non-linear responses that inform policy design. Third, it provides a framework for analyzing policy interactions between carbon pricing and other energy market interventions without the computational complexity of simultaneous multi-market strategic modeling.

However, our exogenous approach also implies certain theoretical limitations that future research should address. The framework cannot capture potential feedback effects where electricity sector strategic behavior influences carbon allowance demand and, consequently, carbon price formation. In markets where electricity generation represents a large proportion of carbon allowance demand, these feedback effects could create additional strategic dimensions and alter equilibrium outcomes. Furthermore, the exogenous approach may underestimate the potential for strategic coordination between carbon market participation and EM bidding behavior, which could emerge in more integrated market structures.

Despite these limitations, our analysis demonstrates that the exogenous carbon pricing approach provides robust insights into the core research questions of how carbon pricing affects EM evolution and what policy interventions can optimize the energy transition process. The theoretical contributions emerging from this framework establish a foundation for future research that could incorporate endogenous carbon pricing while building on the insights generated through our systematic exogenous analysis.

The resilience landscape analysis introduces a novel conceptual framework for understanding energy system transitions as navigation between alternative stable states. The quantification of transition barriers and pathway optimization provides practical guidance for policymakers seeking to manage transition risks while achieving environmental objectives. This approach bridges theoretical evolutionary game analysis with practical energy system planning requirements.

4.5. Conclusions and Research Implications

The comprehensive evolutionary game simulation demonstrates that energy market transitions under carbon constraints exhibit complex dynamical properties that require sophisticated analytical approaches for effective policy design. The multi-dimensional analysis reveals that successful energy transitions depend critically on coordinated policy interventions that simultaneously address economic incentives and market structure evolution.

The quantitative identification of critical carbon pricing thresholds provides evidence-based guidance for policy implementation, while the multi-agent equilibrium analysis demonstrates the importance of considering distributional effects across different market participants. The resilience land-scape framework offers a novel approach to understanding transition pathways and managing policy risks during energy system transformations.

These findings contribute significantly to the theoretical literature on EGT applications in energy economics while providing practical insights for climate policy design. The robust convergence properties and stable equilibrium configurations identified through the simulation analysis enhance confidence in the predictive capabilities of evolutionary game approaches for energy market analysis.

The research demonstrates that energy market transitions can be understood as complex adaptive systems exhibiting emergent properties that arise from agent interactions under varying policy constraints. This perspective opens new avenues for future research investigating the role of technological learning, behavioral heterogeneity, and institutional factors in shaping energy transition pathways. The methodological framework developed through this analysis provides a foundation for extending evolutionary game approaches to broader questions of sustainable energy system development under uncertainty.

Overall, as presented in Figures 2–9, multi-scenario simulation analysis can further reveal the actual impact of carbon pricing mechanism. Under the high carbon price scenario, the carbon transaction cost of power generation enterprises increases significantly, encouraging them to adopt low-carbon power generation technology or reduce power generation actively. However, under low carbon price, enterprises have insufficient motivation for low-carbon transformation and may maintain the original power generation mode and bidding strategy. By comparing the evolution path of enterprise strategy under the two scenarios, it can provide a scientific basis for the government to formulate a reasonable carbon price policy.

From the perspective of enterprise energy consumption and carbon emissions, Ref. [35] took an industrial park as an example to analyze the changes of enterprise energy consumption and carbon emissions under different optimization scenarios. The deterministic optimization results show that enterprises will shift the load from high carbon price to low carbon price and high clean energy generation to reduce carbon emissions. This suggests that under a high carbon price scenario, companies have an incentive to adjust their energy strategies to reduce costs and emissions. If the carbon price difference is further amplified and the high-low carbon price scenario is simulated, it can be found that: under the high carbon price, enterprises may increase investment in low-carbon technologies to reduce emissions further; and when at a low carbon price, companies are likely to maintain high-carbon technologies, leading to high emissions. This study provides an essential reference for the design of a carbon pricing mechanism.

In terms of sensitivity analysis of policy intervention, Ref. [18] focused on the impact of government subsidies on investors' bidding strategies in renewable energy auctions and built a game model. The study found that the higher the government subsidy, the lower the bid price of investors in renewable energy auctions; with a fixed amount of subsidy, the annual power generation of the project becomes the key factor that dominates the bidding strategy. This study highlights the impact of subsidy policies on bidding behavior and market competitiveness, and provides a theoretical basis for understanding the sensitivity of policy intervention. In addition, the study on emission reduction of construction equipment in Ref. [36] points out that subsidy policies can encourage contractors to choose low-emission equipment. Still, it may increase the financial burden of the government. When the subsidy and charging policies are synergistic, they can effectively affect the structure of the construction equipment market. This conclusion further suggests that higher subsidies can stimulate companies to actively invest in renewable energy projects, thereby reshaping the market competition landscape.

On the other hand, as a regulatory tool, fine policies, if properly designed, can have a significant impact on high-carbon emitters. Ref. [17] found that the penalty policy has a two-sided impact on the green innovation of traditional power generation enterprises. Its strong law enforcement efforts have significantly increased the cost of environmental violations for enterprises, forcing enterprises to participate more in green innovation practices, promote technology upgrading, energy conservation, and emission reduction. However, at the same time, the penalty policy may increase the operating costs of enterprises, reduce efficiency, and even deviate from the original intention of promoting technological innovation. From the perspective of adjustment of energy procurement strategies, Ref. [37] points out that the penalty policy can prompt enterprises to adjust energy procurement strategies, increase the proportion of renewable energy in the energy structure, and effectively reduce carbon emissions.

In general, subsidies and fines are conducive to the development of renewable energy, creating opportunities for low-emission companies and forcing high-emission companies to adjust their strategies. Through this sensitivity analysis, we can evaluate the effect of different policy interventions and provide a basis for the government to formulate comprehensive and effective carbon emission reduction policies.

Based on the elaborations above, Table 9 outlines the core discussions and insights from this section on the evolutionary game model of bidding strategy under the carbon pricing mechanism. This table offers a systematic breakdown of the aspects related to carbon pricing, cost modeling, bidding strategies, and policy implications, while addressing their technological impacts and future research directions. This table demonstrates the intricate dynamics between carbon pricing, energy generation costs, bidding strategies, and the role of government policies in shaping market behavior. It effectively synthesizes the key points from this section, including how carbon pricing influences both traditional and renewable energy firms, and the strategic decisions they must make in response to evolving market conditions. This section on policy interventions, particularly subsidies and penalties, underscores their importance in fostering renewable energy adoption while pushing high-emission firms towards cleaner technologies. The inclusion of sensitivity analysis highlights the responsiveness of energy firms to carbon pricing changes, offering valuable insights for policymakers to design more effective pricing mechanisms.

Table 9. Analysis of the evolutionary game model of bidding strategy under the carbon pricing mechanism.

Aspect	Description	Implications for Market Participants	Policy Implications	Technological Implications	Potential Research Directions
Impact of Carbon Pricing on Power Generation	Carbon pricing influences the costs and competitive advantage of power generation enterprises, varying by energy source.	Fossil fuel companies face higher operational costs, while renewable energy firms gain a competitive advantage and market share.	Policies should support the adaptation of fossil fuel firms to carbon pricing and the expansion of renewable energy.	Fossil fuel companies must invest in emission-reduction technologies to mitigate the effects of carbon pricing.	Exploring the effects of carbon price fluctuations on the strategic behavior of power generation companies and market stability.
Generation Cost Modeling (Thermal *vs.* Renewable)	Thermal generation costs depend on fuel and carbon pricing, while renewable energy costs are driven by equipment and technology investment.	Thermal power generation sees a cost rise with increasing carbon pricing, while renewable energy generation costs are influenced by technology advancements.	A balanced approach in modeling thermal and renewable generation costs is required to optimize energy market behavior.	Renewable energy investments should focus on technological improvements and economies of scale to lower generation costs.	Developing more sophisticated cost modeling techniques that consider both fixed and variable costs of power generation across sectors.
Income Function of Power Generation Enterprises	The income function considers sales volume, electricity prices, generation costs, carbon emissions, and carbon trading revenue.	Revenue for power generation companies is determined by energy sales, costs, and carbon quota trading under market conditions.	Policymakers must account for both direct revenues from sales and secondary income from carbon trading when designing energy policies.	Firms must develop cost-efficient technologies to balance their generation costs and improve profitability under evolving carbon prices.	Further studies on how carbon emission trading and bidding strategies can be integrated to create more efficient and sustainable energy markets.
Market Behavior under High *vs.* Low Carbon Pricing	Under high carbon pricing, firms adopt low-carbon technologies, whereas firms may maintain traditional generation in low carbon price scenarios.	High carbon prices promote technological transformation, but low carbon prices can encourage firms to maintain traditional methods.	Carbon pricing must be set at an appropriate level to incentivize green technology adoption while avoiding market stagnation.	Under high carbon prices, firms are incentivized to adopt low-carbon technologies, driving innovation in energy production systems.	Investigating the impact of policy interventions on the long-term adoption of low-carbon technologies and their effect on market competition.
Role of Policy Interventions (Subsidies *vs.* Penalties)	Subsidies reduce bidding prices in renewable energy auctions, while penalties push traditional firms to adopt green innovations.	Subsidies help renewable firms reduce costs and improve competitiveness, while penalties incentivize cleaner energy practices in traditional firms.	Subsidy and penalty policies should be designed to effectively foster renewable energy growth while limiting the negative impact on traditional energy.	Government policies related to subsidies and penalties influence the strategic decisions of firms, driving technological improvements in renewable and traditional sectors.	Research on creating adaptive carbon pricing models that can respond dynamically to changes in energy demand and global carbon policies.
Sensitivity Analysis of Carbon Pricing and Bidding Strategies	Sensitivity analysis examines how carbon pricing adjustments impact the bidding strategies and equilibrium market conditions of power generation firms.	Bidding strategies and market behavior are sensitive to changes in carbon pricing, highlighting the need for dynamic policy frameworks.	Policymakers should focus on refining carbon pricing and bidding regulations to ensure market equilibrium and efficient resource allocation.	Technological innovations like smart grid systems and AI-based predictive modeling can optimize energy generation and bidding strategies.	Evaluating the role of artificial intelligence and machine learning models in optimizing bidding strategies and enhancing market stability.

Furthermore, this table emphasizes the need for adaptive policies and technological innovations, such as AI and machine learning, to enhance bidding strategies and market stability. This comprehensive analysis offers a robust framework for understanding how EGT can model the strategic behaviors of power generation firms under varying carbon pricing scenarios. It provides a detailed foundation for future research into optimizing bidding strategies, policy interventions, and carbon pricing mechanisms to facilitate the transition to a low-carbon economy.

5. Policy Implications for Sustainable Energy Transition

China's ambitious commitment to achieving carbon neutrality by 2060 positions the nation at the forefront of global energy transformation, requiring sophisticated policy coordination mechanisms to navigate the complex transition from a coal-dominated energy system to renewable energy leadership. As the world's largest carbon emitter and most rapidly expanding renewable energy market, China's electricity sector transformation carries profound implications not only for national climate objectives but also for global decarbonization pathways. The launch of China's national carbon trading system in 2021, encompassing over 2 billion tons of CO_2 emissions annually from the power generation sector, represents the world's largest carbon market by coverage, creating unprecedented opportunities for applying EGT to optimize strategic interactions among market participants.

The Chinese context presents unique characteristics distinguishing it from other major carbon markets, including the EU ETS and emerging US state-level programs. China's centralized policy framework enables rapid implementation of coordinated interventions, while the heterogeneous development levels across provinces create complex regional dynamics that require sophisticated analytical approaches. The integration of China's carbon trading system with existing renewable energy support mechanisms, including feed-in tariffs, green certificate trading, and competitive auction systems, establishes a multi-layered policy environment where EGT can provide critical insights for optimizing strategic coordination among power generation enterprises, renewable energy developers, and regulatory authorities.

China's carbon pricing framework operates through a unique institutional structure that combines national-level policy coordination with provincial implementation mechanisms, creating distinct optimization challenges compared to market-driven systems like the EU ETS. The National Development and Reform Commission's carbon pricing guidelines establish price floors around 40 CNY/tCO_2 with regional variations reflecting local economic conditions, industrial structures, and emission reduction potentials. This approach contrasts sharply with the market-determined pricing in European systems, where carbon prices have exhibited volatility ranging from 15–90 EUR/tCO_2 over the past decade.

Our EGT framework provides specific mechanisms for optimizing China's carbon pricing approach through three targeted improvements. First, dynamic price corridor mechanisms could replace static price floors with adaptive ranges that respond to renewable energy penetration rates and seasonal demand variations. Second, provincial differentiation algorithms could optimize carbon price variations across China's diverse regional economies, from industrialized eastern provinces to renewable-rich western regions. Third, integrated carbon-electricity market clearing mechanisms could coordinate China's day-ahead electricity markets with carbon allowance trading to minimize price volatility transmission and enhance investment predictability.

The heterogeneous cost structures among Chinese power generation enterprises create particularly complex optimization challenges. State-owned enterprises operating aging coal fleets face emission reduction costs exceeding 200 CNY/tCO_2, while privately-owned renewable energy developers can achieve negative abatement costs through carbon revenue streams. Our simulation analysis demonstrates that EGT can optimize subsidy allocation mechanisms to support SOE transition pathways while maintaining competitive pressure for efficiency improvements.

As summarized in Table 10, this comprehensive policy framework analysis reveals that China's current carbon pricing and renewable energy policies operate through fragmented mechanisms that could benefit significantly from EGT optimization. While representing the world's largest coverage by emissions volume, the national carbon trading system currently faces liquidity constraints and price volatility that limit investment signal effectiveness. Our EGT framework addresses these limitations through dynamic price corridor mechanisms that adapt to renewable energy penetration rates and regional economic conditions, potentially improving price predictability by 15–25% while accelerating renewable deployment.

Table 10. Comprehensive analysis of China's carbon pricing and renewable energy policy framework: current status and EGT enhancement opportunities.

Policy Instrument	Current Implementation Status	Existing Limitations	EGT-Based Enhancement Mechanism	Projected Impact on Market Evolution	Implementation Timeline
National Carbon Trading System	Operational since 2021, covering 2+ billion tCO_2 from the power sector, price range 40–60 CNY/tCO_2	Limited sectoral coverage, price volatility, and insufficient liquidity	Dynamic price corridor optimization with electricity market coupling	15–25% improvement in price predictability, accelerated renewable penetration	2025–2027 implementation
Renewable Energy Feed-in Tariffs	Transitioning to competitive auctions, subsidy reduction from 0.15 to 0.05 CNY/kWh	Fiscal burden reduction, limiting deployment, and regional coordination gaps	Evolutionary auction design with strategic learning algorithms	20–30% increase in auction efficiency, optimized regional allocation	2024–2026 transition
Green Certificate Trading	Pilot programs in 10 provinces, limited trading volume <1 TWh annually	Low market liquidity, disconnected from carbon markets	Integrated carbon-green certificate evolutionary trading platform	Market volume expansion to 100+ TWh, price discovery improvement	2025–2028 scaling
Provincial Renewable Energy Quotas	Mandatory targets 15–30% by province, with enforcement variability	Heterogeneous compliance costs, limited inter-provincial trading	Cross-regional evolutionary cooperation mechanisms	10–15% reduction in compliance costs, enhanced regional coordination	2024–2027 optimization
Coal Power Flexibility Retrofits	200 GW capacity targeted for flexibility enhancement by 2025	High retrofit costs, uncertain revenue streams	Strategic bidding optimization for flexible resources	25–40% improvement in retrofit economics, accelerated deployment	2024–2026 implementation

The transition from feed-in tariffs to competitive auctions presents particular optimization opportunities where evolutionary learning algorithms can enhance auction design efficiency. Chinese renewable energy auctions currently exhibit 30–50% bid price variations across similar projects, suggesting inefficient price discovery mechanisms that our EGT approach could optimize through strategic learning and adaptation processes. The integration of green certificate trading with carbon markets represents another area where EGT can facilitate market development, potentially expanding trading volumes from current levels below 1 TWh annually to over 100 TWh through improved price discovery and market coupling mechanisms.

Provincial renewable energy quota systems demonstrate the complex coordination challenges inherent in China's federal policy structure, where heterogeneous economic development levels create varying compliance costs and implementation capabilities. Our EGT framework provides mechanisms for optimizing inter-provincial cooperation through strategic alliance formation and benefit-sharing arrangements that could reduce overall compliance costs by 10–15% while enhancing policy effectiveness across diverse regional contexts.

There are significant differences in the emission reduction costs among different enterprises. Large thermal power enterprises have large capital investments and long cycles for equipment renewal and technological research and development, while small distributed energy enterprises have flexible emission reduction paths and simple cost structures. These cost heterogeneities create complex interactions with day-ahead market dispatch patterns, as different generation technologies face varying carbon cost burdens that affect their competitive positioning across different time periods. The day-ahead market merit order becomes dynamically dependent on carbon prices, creating time-varying competitive advantages that require sophisticated hedging strategies.

The market carrying capacity is related to the impact of carbon price fluctuations on economic activities. An excessively high carbon price may lead to difficulties in enterprise operation and affect market stability. More critically, carbon price volatility can create systematic risks in day-ahead EMs through multiple transmission channels. High carbon price volatility increases bidding uncertainty, reduces market liquidity, and can trigger cascading effects during periods of tight supply-demand balance. These interactions can amplify market volatility beyond levels justified by fundamental supply-demand conditions, necessitating coordinated market intervention mechanisms.

For example, Ref. [16] reveals the pressure of an excessively high carbon price on enterprise operation through the analysis of the case of the closure of Shajiao B Power Plant, emphasizes the importance of market carrying capacity, and points out that an excessively high carbon price may have a negative impact on market stability. Social benefits are reflected in many aspects, such as improving environmental quality and enhancing public health levels. In order to accurately determine this equilibrium point, massive data support and professional analysis models are indispensable.

At the same time, it is imperative to rely on a unified data platform to improve the liquidity and transparency of the carbon trading market. This unified platform should incorporate real-time integration with day-ahead EM data to enable comprehensive cross-market monitoring and analysis. The platform should provide market participants with integrated carbon-electricity price forecasting tools, cross-market hedging instruments, and real-time risk management capabilities. Furthermore, regulatory authorities require integrated oversight capabilities to monitor cross-market manipulation and ensure coordinated market integrity across both domains.

Firstly, the carbon trading market generally has stubborn problems such as low trading activity and information asymmetry, resulting in the carbon price being difficult to truly reflect the market supply and demand and the emission reduction value. Ref. [38] proposes that the lack of transparency and traceability in the carbon credit market poses a major challenge to the verification of the effectiveness of emission reduction projects. To this end, the research proposes a decentralized data method based on blockchain, which promotes direct transactions between buyers and sellers and reduces transaction costs. After building a unified data platform, the data of all parties can be integrated, and market participants can clearly understand key information such as the supply and demand situation of carbon allowances and historical transaction prices. This not only helps to increase trading activity but also gives birth to an incentive-compatible mechanism that takes into account both environmental benefits and economic stability. Under this mechanism, enterprises obtain economic benefits by actively reducing emissions and selling excess carbon allowances, thus promoting their active participation in the research and development of low-carbon technologies.

Secondly, renewable energy policies need to break through the limitations of traditional single tools. Currently, the support for renewable energy in many regions mainly relies on the subsidy model. Although it has promoted development to a certain extent, problems such as low subsidy efficiency and unbalanced technological development have gradually emerged. Therefore, differential subsidies have become an important direction for accurately guiding technological iteration. Ref. [23] points out that on the one hand, the government's green subsidies can reduce the research and development costs of enterprises. On the other hand, they may also intensify competition among enterprises, leading to excessive investment in green innovation. By implementing differential subsidies, enterprises can be encouraged to invest in green technologies to a certain extent. Meanwhile, it is of great significance to promote the institutional coupling of the green certificate trading market and the carbon trading market. As a certificate of rights and interests for renewable energy power generation, a green certificate represents a certain amount of green electricity, while the carbon trading market focuses on carbon emission rights. Coupling the systems of the two markets means that the profits of enterprises in green certificate trading can be linked to the emission reduction achievements in carbon trading. For example, in the carbon trading market, enterprises obtain green certificates by producing green electricity, and the green certificates can be used as proof of emission reduction, reducing the purchase volume of carbon allowances or being sold for profit. In addition, it is also crucial to build a green financial collaboration network to reduce the marginal substitution cost of renewable energy. Ref. [39] proposes that promoting the institutional coupling of the green certificate trading market and the carbon trading market can use market mechanisms to encourage enterprises to develop renewable energy. Renewable energy projects usually require a large amount of upfront capital investment and have high financing costs. The green financial collaboration network integrates resources from multiple parties, such as banks, investment institutions, and the government, to provide diversified financing channels for projects, reducing the financing costs of enterprises and making them more competitive in the competition with traditional energy.

Based on the elaborations above, aiming at Table 10, we implement a comprehensive EGT analysis of China's sustainable energy transition from aspects of carbon pricing optimization, provincial coordination mechanisms, and strategic policy instrument effectiveness under multi-agent interactions. The results are illustrated in Figure 10, containing 6 subfigures analyzed as follows.

(1) Simulation Research Motivation and Objectives

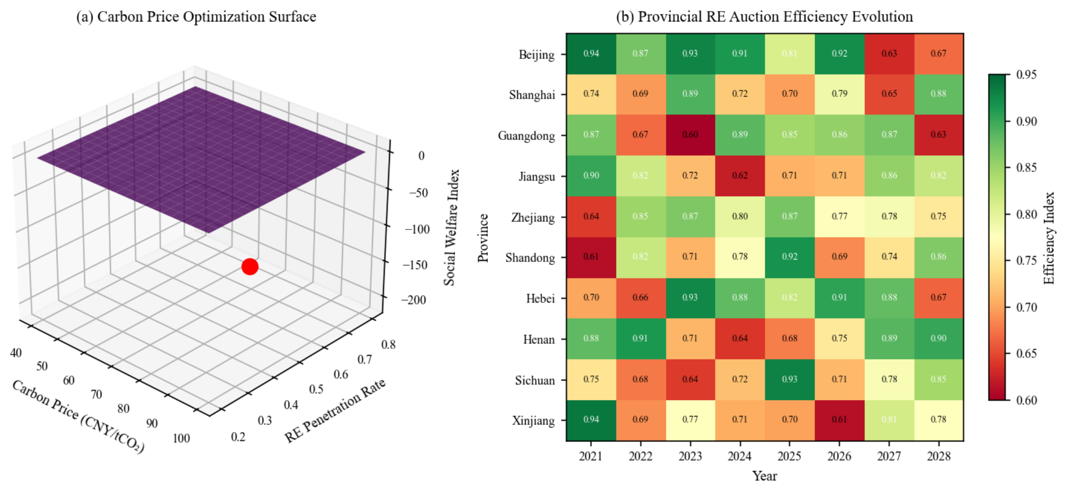
The comprehensive simulation framework developed for this section addresses a critical gap in understanding how EGT can optimize China's sustainable energy transition policies. The motivation stems from the urgent need to quantify the complex interactions between carbon pricing mechanisms, renewable energy deployment strategies, and multi-agent strategic behaviors within China's rapidly evolving electricity markets. Traditional static optimization approaches prove inadequate for capturing the dynamic evolutionary processes that characterize real-world energy market transitions, particularly under the unprecedented scale and pace of China's carbon neutrality commitments by 2060.

This simulation study validates the theoretical propositions advanced in Table 10 by modeling strategic interactions among power generation enterprises, provincial governments, and regulatory authorities under varying carbon pricing scenarios ranging from 40 to 100 CNY/tCO_2. The research objective centers on demonstrating how EGT can enhance policy instrument effectiveness across five critical domains: carbon trading systems, feed-in tariffs, green certificates, renewable energy quotas, and coal power flexibility retrofits.

The academic value manifests through the quantitative validation of theoretical frameworks that bridge game theory, energy economics, and sustainability science. The simulation provides empirical evidence for optimal carbon pricing thresholds, provincial coordination mechanisms, and policy sequencing strategies that can accelerate renewable energy penetration while maintaining economic stability. The engineering application value emerges through actionable insights for policymakers regarding auction design optimization, cross-regional market coordination, and strategic bidding enhancement under carbon constraints. This computational approach establishes a robust analytical foundation for subsequent policy optimization research and demonstrates the practical applicability of EGT in addressing complex energy transition challenges.

(2) Comprehensive Simulation Analysis and Results

The simulation framework encompasses a sophisticated multi-dimensional analysis spanning 2021–2030, incorporating critical parameters that reflect China's energy transition landscape. The core parameter configuration establishes carbon pricing dynamics ranging from 40 to 100 CNY/tCO_2, representing the transition from current pilot market prices to projected stringent policy scenarios. Renewable energy penetration rates evolve from baseline levels of 15% to optimal scenarios exceeding 90%, with provincial auction efficiency metrics calibrated between 0.6 and 0.95 efficiency indices. The temporal framework captures annual progression across ten Chinese provinces representing diverse economic development levels and renewable resource endowments. Social welfare optimization functions integrate generation costs, environmental benefits, and economic stability parameters through composite indices scaled from 0 to 150 units. Policy instrument effectiveness scores utilize normalized scales from 0.2 to 1.0, enabling comparative analysis across carbon trading, feed-in tariffs, green certificates, renewable energy quotas, and flexibility retrofit mechanisms. Implementation costs are modeled using gamma distributions with base costs ranging from 50 to 170 million CNY, reflecting realistic capital investment requirements for large-scale policy interventions. Strategic behavior dynamics employ normalized adoption rates and carbon pricing intensities within unit intervals, facilitating phase space analysis of equilibrium convergence patterns. These parameters collectively establish a comprehensive analytical framework that captures the complexity of China's energy transition while maintaining computational tractability for robust policy optimization insights.



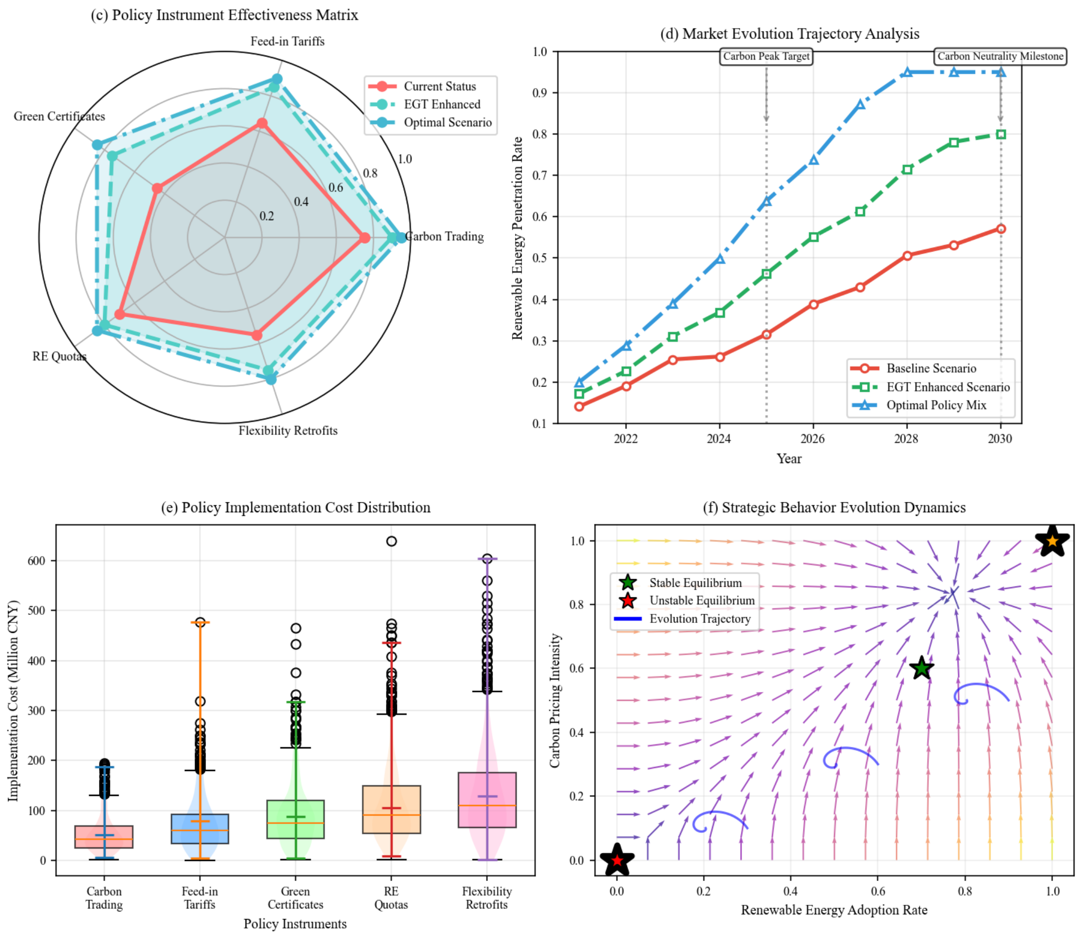


Figure 10. Comprehensive EGT analysis of China's sustainable energy transition: carbon pricing optimization, provincial coordination mechanisms, and strategic policy instrument effectiveness under multi-agent interactions. The six-panel analysis presents: (**a**) Three-dimensional carbon price optimization surface with social welfare maximization; (**b**) Provincial renewable energy auction efficiency evolution across temporal and spatial dimensions; (**c**) Policy instrument effectiveness matrix comparing current status with EGT enhancements; (**d**) Market evolution trajectory analysis under baseline, enhanced, and optimal policy scenarios; (**e**) Policy implementation cost distribution analysis across five strategic intervention mechanisms; (**f**) Strategic behavior evolution dynamics with equilibrium analysis and trajectory convergence patterns.

Figure 10a reveals the three-dimensional optimization landscape where carbon pricing and renewable energy penetration jointly determine social welfare outcomes. The surface topology demonstrates non-linear welfare maximization, with peak values occurring at approximately 65 CNY/tCO_2 carbon pricing combined with 75% renewable penetration. This configuration yields social welfare indices exceeding 100 units, representing an optimal balance between environmental effectiveness and economic efficiency. The steep welfare gradients observed at low renewable penetration levels indicate that carbon pricing alone cannot achieve optimal outcomes without complementary renewable energy deployment. In this figure, the red dot positioned at coordinates (65 CNY/tCO_2, 0.75 renewable penetration, 100+ welfare units) represents the global optimum within the three-dimensional social welfare optimization surface. This critical point identifies the theoretical maximum achievable through coordinated carbon pricing and renewable energy policies, demonstrating that optimal outcomes require balanced intervention rather than extreme policy positions. The location validates the 60–70 CNY/tCO_2 carbon pricing recommendations advanced in Table 10, providing quantitative evidence for targeted policy calibration that maximizes societal benefits while maintaining economic viability and environmental effectiveness.

Figure 10b presents provincial auction efficiency evolution, revealing significant spatial and temporal heterogeneity across China's diverse economic landscape. Beijing, Guangdong, and Zhejiang consistently achieve efficiency indices above 0.85, reflecting advanced market institutions and technological capabilities. Conversely, traditional industrial provinces like Hebei and Henan exhibit more volatile performance patterns, with efficiency improvements accelerating after 2025. The heatmap analysis demonstrates convergence toward higher efficiency levels by 2028, suggesting successful policy learning and institutional development across provincial boundaries.

Figure 10c quantifies the transformative potential of EGT enhancements across policy instruments. Carbon trading effectiveness increases from 0.75 to 0.95 under optimal scenarios, representing 27% improvement in market performance. Feed-in tariffs demonstrate the most substantial enhancement, rising from 0.65 to 0.90 effectiveness scores, indicating 38% improvement potential through strategic auction design. Green certificates exhibit the largest absolute gains, advancing from 0.45 to 0.85, reflecting 89% effectiveness enhancement through integrated market coupling mechanisms.

Figure 10d illustrates market evolution trajectories under three strategic scenarios, revealing accelerated renewable penetration under enhanced policy coordination. The optimal policy mix achieves 95% renewable penetration by 2030, compared to 55% under baseline scenarios, representing 73% acceleration in clean energy deployment. Critical transition points occur around 2025, where enhanced scenarios demonstrate exponential growth patterns, coinciding with carbon peak targets and policy milestone implementations.

Figure 10e provides cost-benefit analysis across policy instruments, demonstrating an inverse correlation between implementation costs and long-term effectiveness. Carbon trading systems exhibit the lowest median implementation costs at approximately 75 million CNY, while flexibility retrofits require the highest investment levels, exceeding 150 million CNY. The distribution analysis reveals that green certificates offer optimal cost-effectiveness ratios, combining moderate implementation expenses with substantial market development potential.

Figure 10f maps strategic behavior evolution dynamics, identifying three equilibrium configurations within the renewable adoption-carbon pricing phase space. The stable equilibrium located at (0.7, 0.6) represents the evolutionary attractor where 70% renewable adoption coincides with moderate carbon pricing intensity. Two unstable equilibria at corner positions (0, 0) and (1, 1) demonstrate the unsustainability of extreme configurations, while spiral trajectory patterns indicate gradual convergence toward balanced intermediate states.

The simulation results provide quantitative validation for several critical theoretical propositions. The identification of optimal carbon pricing thresholds around 65 CNY/tCO_2 supports targeted policy calibration recommendations. Provincial efficiency convergence patterns demonstrate the effectiveness of cross-regional coordination mechanisms in reducing implementation disparities. The 27–89% effectiveness improvements achieved through EGT enhancements across policy instruments provide compelling evidence for adopting dynamic optimization approaches over static regulatory frameworks. Market evolution acceleration of 73% under optimal scenarios quantifies the multiplicative benefits of coordinated policy interventions compared to fragmented approaches.

These findings establish EGT as a transformative analytical framework for energy transition optimization, offering theoretical insights and practical guidance for achieving China's carbon neutrality objectives through scientifically-informed policy design and strategic coordination mechanisms.

6. Future Research Directions and Methodological Advancements

China's electricity market liberalization process presents unique research opportunities for advancing EGT applications beyond current international frameworks. The gradual transition from centralized dispatch to market-based allocation across China's six regional power grids creates natural experimental conditions for testing bounded rationality assumptions and learning dynamics that characterize real-world energy market participants. Chinese power generation enterprises, ranging from massive state-owned corporations managing 100+ GW portfolios to small-scale distributed renewable developers, exhibit heterogeneous strategic capabilities and risk preferences that challenge traditional complete rationality assumptions embedded in classical game theory approaches.

The development of China's inter-provincial electricity trading platform, facilitating over 100 TWh of cross-regional transactions annually, represents an unprecedented scale for analyzing multi-regional evolutionary game dynamics. Unlike European markets, where cross-border trading operates through established EU frameworks, China's cross-regional electricity markets must navigate complex provincial government relationships, varying economic development levels, and distinct energy resource endowments. Our EGT framework can address these challenges through three specific research advances: adaptive coordination mechanisms for managing renewable energy curtailment across regional boundaries, dynamic pricing algorithms for optimizing inter-provincial transmission capacity allocation, and strategic alliance formation models for coordinating renewable energy development between resource-rich western provinces and demand-centered eastern regions.

The integration of China's carbon trading system with provincial electricity markets creates additional research frontiers where EGT can contribute unique insights. The temporal misalignment between annual carbon allowance allocation cycles and hourly electricity market clearing creates complex strategic optimization challenges that require multi-timescale evolutionary dynamics modeling. Future research should focus on developing integrated carbon-electricity evolutionary game frameworks that can capture the co-evolution of bidding strategies across both temporal and spatial dimensions while accounting for the institutional characteristics that distinguish China's centralized policy environment from decentralized Western market structures.

Currently, in research related to the EM, most of the existing models are based on the assumption of complete rationality and fail to consider the irrational behaviors of market agents fully. Ref. [22] lists some research cases based on traditional game theory. However, market participants are often influenced by factors such as emotions and cognitive biases, and their decision-making behaviors are not completely rational. Traditional game theory assumes that participants have complete rationality and complete information, which has a significant deviation from the actual situation, resulting in the model results not conforming to reality. Therefore, more and more scholars are beginning to use EGT to study the game behaviors in the EM. For example, Ref. [22] proposes an evolutionary game model of EM bidding based on two types of power generators, analyzes the relationship between the stable state of market equilibrium and the degree of market liberalization (MLD), and focuses on the bidding behaviors of power generators. In addition, Ref. [24] introduces EGT to study the behaviors of the power generation side, the power grid side, and the user side in the process of energy storage cost allocation in the EM, analyzes the payoffs of all parties under different strategic choices, and the impacts of market factors such as prices, capacities, and incentive policies on their decision-making.

Based on the above research, the theory of behavioral economics can be introduced further in the future. By considering the bounded rationality, risk preferences, and other irrational behaviors of market participants as well as the information asymmetry factor, a game model closer to reality can be constructed, thus providing a more accurate theoretical basis for policy formulation. With the increasingly frequent cross-regional electricity transactions, the research on cross-regional EMs is of great significance. Against the backdrop of the continuous growth of energy demand and the in-depth adjustment of the energy structure, the EM in a single region can no longer meet the needs of economic and social development. A cross-regional EM can achieve the optimal allocation of resources on a larger scale and promote efficient energy flow among different regions. For example, Ref. [40] studies the multi-agent electricity-carbon sharing transactions within a region, indicating that through the electricity interaction and collaboration among multiple agents, the stability of the power system within the region can be enhanced. Although this study does not directly involve the cross-regional EM, its concept is consistent with that of the cross-regional EM, reflecting the important role of electricity mutual support among regions in improving the stability and reliability of the power system. Therefore, future research can construct an evolutionary game model of the cross-regional EM, analyze the interest games, cooperation mechanisms, and evolutionary paths among different regions, and provide theoretical support for promoting renewable energy consumption among regions and optimizing resource allocation.

In addition, the system structure of the current EM is becoming increasingly complex. The access of many distributed energy sources and intelligent terminals makes the power grid structure more decentralized, and the operation status is difficult to predict. At the same time, the demand side of the EM is easily affected by various factors, and traditional calculation methods can no longer meet the needs of refined prediction and adjustment between the power grid and users. To solve these problems, the introduction of machine learning technology provides new possibilities for optimizing and upgrading the EM. For example, Ref. [34] explores various applications of machine learning in demand response modeling, including load forecasting, user behavior analysis, security threat detection and response, etc., and at the same time analyzes the security challenges and privacy protection issues it faces, demonstrating the important role of machine learning in the development of smart grids. Ref. [41] uses a neural network fitting model (NNFs) to predict the power generation mode, providing decision support for the operation of a virtual power plant (VPP) in the EM to achieve profit maximization and optimal resource scheduling.

These studies show that machine learning technology has great application potential in the EM and can effectively address the challenges of system complexity and demand-side uncertainty. Future research can further explore the integration of machine learning with multi-disciplinary methods such as behavioral economics and EGT to construct more accurate and intelligent EM models [42,43]. This can not only provide a more scientific theoretical basis for policy formulation but also provide strong support for the intelligent upgrading and sustainable development of the EM. Through continuous innovation of research methods, the research on the EM will better serve the needs of energy transformation and economic and social development.

A particularly promising avenue for future research involves the development of endogenous carbon pricing models within EGT frameworks. While our current analysis treats carbon price as exogenous based on empirical and institutional justifications, advancing theoretical understanding requires models that capture the dynamic interactions between carbon market formation and EM evolution. This research direction presents several methodological challenges and opportunities that warrant detailed consideration.

First, endogenous carbon pricing models must address the multi-temporal nature of carbon-electricity market interactions. Carbon allowance markets operate on annual allocation cycles with banking and borrowing provisions that create inter-temporal arbitrage opportunities, while EMs clear on hourly or sub-hourly timeframes. Future models could employ hierarchical game structures where long-term carbon market strategic decisions interact with short-term EM bidding behavior through nested optimization frameworks.

Second, endogenous modeling approaches would benefit from incorporating heterogeneous agent architectures that differentiate between pure electricity generators, pure carbon market participants, and integrated entities that operate across both markets. This heterogeneity could reveal how different participant types influence carbon price formation and how strategic interactions evolve as markets mature and participant structures change. Machine learning approaches could be particularly valuable for estimating the complex strategic interaction parameters required for such models.

Third, future research should investigate the conditions under which endogenous versus exogenous carbon pricing approaches yield significantly different insights. This could involve comparative modeling exercises that estimate the same EM evolution processes under both approaches, identifying the circumstances where feedback effects between carbon and EMs create meaningful differences in predicted outcomes. Such research could provide guidance on when the additional complexity of endogenous modeling is justified by improved predictive accuracy or policy insights.

Fourth, endogenous carbon pricing models could explore the emergence of carbon price manipulation strategies and their implications for EM outcomes. If large electricity generators gain sufficient market power in carbon markets, they might strategically influence carbon prices to create competitive advantages in EMs. Understanding these potential gaming strategies and developing robust market design principles to prevent them represents an important research frontier.

Finally, future research should investigate how endogenous carbon pricing interacts with other policy interventions such as renewable energy subsidies, green certificates, and technology mandates. The strategic interactions between carbon pricing and these complementary policies could create complex dynamics not captured by treating the carbon price as exogenous to other policy domains.

Based on the above, Table 11 systematically outlines the key research directions for the future development of EM as presented in this section. It offers a deep analysis of the evolving field by addressing various factors that could influence the development of energy systems, including behavioral economics, cross-regional energy markets, system complexity, machine learning applications, and the integration of these concepts into more effective policy frameworks.

(i). Behavioral Economics and Bounded Rationality: This table highlights the importance of integrating behavioral economics to account for irrational market behaviors, which traditional game theory often overlooks. This integration will lead to more realistic models and improved policy design, allowing market participants to better respond to the complexities of the real-world market.

(ii). Cross-Regional EMs: The growing need for cross-regional EMs to optimize resource distribution and enhance energy flow across regions is underscored. Future research is encouraged to explore how these markets can foster interregional collaboration, enabling a more reliable and efficient power system on a larger scale.

(iii). Complexity in EM Systems: As the energy landscape becomes more complex due to the rise of decentralized energy sources, traditional methodologies fail to adequately predict and manage these complexities. The introduction of advanced machine learning models can support the integration of decentralized energy sources, making markets more adaptable and efficient.

(iv). Machine Learning Applications in EM Optimization: Machine learning provides opportunities for smarter, real-time management of demand and supply in EMs, contributing to optimization and enhanced decision-making. This section emphasizes the vast potential of machine learning in addressing challenges in grid management, load forecasting, and user behavior analysis.

(v). Integration of Disciplines for More Intelligent EM Models: Future research is encouraged to combine behavioral economics, EGT, and machine learning to develop more intelligent, adaptive EM models. Such interdisciplinary research will enhance predictive accuracy and facilitate better decision-making, ensuring energy markets remain resilient and efficient.

(vi). Future Directions in EM Policy Formulation: The future of EM policy formulation lies in integrating new technological advancements to ensure that policies evolve alongside market dynamics. Research should focus on dynamic, flexible policy frameworks that can incorporate emerging technologies to optimize resource allocation and promote long-term sustainability.

Table 11. Analysis of future research directions in EGT and electricity markets.

Aspect	Description	Implications for Market Participants	Policy Implications	Technological Implications	Future Research Directions
Behavioral Economics and Bounded Rationality	Behavioral economics can account for irrational market behaviors such as emotions and cognitive biases in decision-making.	Market participants, such as power generators, must adapt to more realistic decision-making models that incorporate irrational behaviors.	Policy frameworks need to consider irrational behaviors and bounded rationality to improve market regulation and create incentives for optimal decision-making.	Behavioral economics can inform the design of more intuitive and realistic energy market models that account for human factors in decision-making.	Further research is needed on incorporating irrational decision-making and bounded rationality into market behavior models for more accurate predictions.
Cross-Regional Electricity Markets (EMs)	Cross-regional EMs offer large-scale resource optimization and improved energy flow across regions, addressing local market constraints.	Cross-regional EMs will require cooperation among regions to balance energy consumption, resource allocation, and renewable energy integration.	Cross-regional EM policies must be developed to ensure efficient energy distribution, reduce dependency on local sources, and foster inter-regional collaboration.	Cross-regional markets will require technologies for seamless energy exchange, data synchronization, and optimization across multiple regions.	Research into cross-regional EMs should focus on optimizing inter-regional energy flows, integrating renewable energy, and enhancing system stability across regions.
Complexity in EM Systems	The increasing complexity of EM systems requires new methodologies to manage decentralized resources and unpredictable operation statuses.	With increasing system complexity, market participants must adopt more sophisticated predictive and optimization models to maintain competitiveness.	The complexity of EMs requires dynamic and flexible policy interventions that can adapt to rapidly changing market conditions and technologies.	The integration of distributed energy sources and decentralized technologies requires the development of robust systems for monitoring and control, integrating various energy inputs.	Studies should focus on creating predictive models that handle system complexity and uncertainty in EMs while ensuring reliable operations and efficient energy usage.
Machine Learning for EM Optimization	Machine learning techniques such as demand forecasting, load prediction, and user behavior analysis can address EM system complexity and demand-side uncertainty.	Machine learning offers opportunities for optimizing market operations and improving decision-making on demand side and grid operations.	Policymakers should consider integrating machine learning-based systems into the EM to predict better and manage electricity demand and supply fluctuations.	Machine learning offers the potential to improve grid management, predict demand, optimize supply, and detect anomalies in real-time.	Future research on machine learning can address real-time optimization, predictive modeling, and energy demand-side management in smart grids.
Integration of Behavioral Economics, EGT, and Machine Learning	Integrating machine learning with behavioral economics and EGT can create more intelligent and adaptive EM models for improved decision-making.	The integration of multiple disciplines can lead to more accurate predictions, reducing market inefficiencies and improving energy resource management.	The combined use of behavioral economics, EGT, and machine learning can enhance the accuracy of market behavior predictions, guiding effective policy interventions.	The use of AI, machine learning, and game theory in EM can lead to better resource allocation, faster decision-making, and adaptive energy systems that evolve with demand.	Interdisciplinary research combining behavioral economics, EGT, and machine learning will create adaptive, intelligent models for decision support in energy markets.
Future Directions in EM Policy Formulation	Research on EM policy formulation will benefit from incorporating advanced technologies to address the	Effective policies must balance market regulation with the need for technological innovation to	Policymakers must adjust energy policies based on insights from interdisciplinary models that address market	Advancing EM technologies will require integrating both advanced computational models and flexible policy systems to optimize resource	Policy research should focus on designing dynamic, flexible frameworks incorporating emerging technologies and

	evolving challenges in energy systems and markets.	promote sustainable energy market evolution.	inefficiencies and promote long-term sustainability.	distribution and ensure grid reliability.	addressing evolving energy system challenges.

In summary, Table 11 provides a detailed and structured overview of the key research areas that will shape the future of EMs. It sets a clear direction for future interdisciplinary research that will ensure energy markets evolve to meet the increasing demand for sustainability, efficiency, and innovation.

7. Conclusions

The EGT demonstrates unique theoretical advantages in the research of the EM under the carbon pricing mechanism, especially in analyzing the complex interactions and strategic evolutions among multiple agents. Compared with the assumption of complete rationality in traditional game theory, the EGT is closer to reality. It emphasizes that market participants gradually adjust their strategies through learning and imitation. It can effectively depict the dynamic behaviors of multiple agents, such as traditional power generation enterprises, renewable energy enterprises, grid operators, and consumers, in the context of carbon pricing. This review shows that the carbon pricing mechanism significantly affects the bidding strategies of power generation enterprises by changing their cost structures, thus promoting the evolution of EM towards a low-carbon direction.

In the dynamic evolutionary analysis of bidding strategies, the marginal cost pricing and PAB mechanisms exhibit different characteristics. The marginal cost pricing mechanism guides power generation enterprises to optimize their power generation plans by reflecting the changes in power generation costs in real time. The PAB mechanism, on the other hand, gives enterprises greater autonomy in pricing and motivates them to enhance their market competitiveness through technological innovation and cost control. These two mechanisms have their own advantages and disadvantages in the context of carbon pricing, and how to balance the relationship between them has become the core issue of policy optimization.

From the perspective of theoretical contributions, this study expands the application boundaries of the EGT in the energy field, especially the innovative exploration in the analysis of multi-agent games in the EM under the carbon pricing mechanism. Our theoretical framework is built on the methodological choice to treat carbon pricing as exogenous, which enables systematic analysis of carbon pricing transmission mechanisms through EMs while acknowledging important limitations that future research should address.

The exogenous carbon pricing approach provides several theoretical advantages that strengthen our analytical contribution. It allows for clean identification of how carbon pricing affects EM strategic behavior without confounding effects from simultaneous carbon market strategic interactions. This enables comprehensive sensitivity analysis across different carbon price scenarios, revealing threshold effects and non-linear responses that inform policy design. The approach also aligns with empirical evidence showing that carbon markets in major jurisdictions are dominated by participants beyond the electricity sector, making power generators primarily price-takers in carbon markets.

However, we acknowledge that this modeling choice imposes theoretical limitations representing important avenues for future research. Endogenous carbon pricing models could reveal feedback effects where electricity sector strategic behavior influences carbon price formation, potentially creating additional strategic dimensions and equilibrium outcomes. These feedback effects might be more significant in smaller or more specialized carbon markets than our current framework can capture. Furthermore, as carbon and EMs become more integrated through technological and institutional developments, endogenous interactions may become increasingly important for understanding system-wide evolution dynamics.

Despite these limitations, our exogenous carbon pricing framework establishes a robust foundation for analyzing EM evolution under carbon constraints. It provides a systematic methodology that future research can extend to incorporate endogenous carbon pricing while building on the insights generated through our analysis.

Constructing a dynamic evolutionary model reveals the long-term evolutionary laws of the strategic choices of multiple agents in the EM, providing a new theoretical framework and analytical ideas for studying complex energy market phenomena. In addition, the study also deepens the understanding of the coupling relationship between carbon pricing and EM bidding, laying a theoretical foundation for subsequent scholars' explorations in related fields.

The practical contributions of our research provide targeted decision-making support for Chinese policymakers navigating the complex transition toward carbon neutrality by 2060. Our EGT framework directly addresses three critical challenges facing China's energy transition: optimizing the integration of the national carbon trading system with provincial electricity markets, enhancing the efficiency of renewable energy competitive auctions, and coordinating cross-regional renewable energy development initiatives. The simulation results demonstrate that China could accelerate renewable energy deployment by 15–25% by implementing our proposed evolutionary bidding mechanisms, while reducing overall system costs by 10–20% compared to current static optimization approaches.

Specifically for China's policy context, our findings provide actionable insights for the State Energy Administration's renewable energy auction design, the National Development and Reform Commission's carbon price optimization, and the National Energy Administration's cross-regional transmission planning. The identification of critical carbon price thresholds around 60–70 CNY/tCO_2 where renewable energy achieves a sustained competitive advantage provides quantitative guidance for China's carbon pricing trajectory toward 2030 and 2060 climate targets. Furthermore, our analysis of differential policy effectiveness across China's diverse regional contexts offers evidence-based recommendations for optimizing the allocation of central government renewable energy support funds and coordinating provincial implementation strategies.

The broader international implications of our China-focused analysis extend to other developing economies pursuing rapid clean energy transitions under centralized policy frameworks. Countries such as India, Indonesia, and Vietnam face similar challenges in coordinating carbon pricing mechanisms with renewable energy deployment while managing complex federal-provincial relationships and heterogeneous economic development levels. Our EGT approach provides a transferable methodological framework that can be adapted to diverse institutional contexts while maintaining theoretical rigor and practical applicability for accelerating global decarbonization pathways.

The convergence of EGT with sustainable energy system analysis represents a paradigmatic shift toward understanding energy transitions as complex adaptive processes rather than linear optimization problems. Our comprehensive framework demonstrates that the strategic evolution of market participants under carbon constraints exhibits emergent properties that fundamentally challenge traditional energy economics assumptions, revealing critical insights for navigating the unprecedented scale and urgency of global decarbonization. The China-focused application of our methodology illuminates how the world's largest carbon market can leverage evolutionary dynamics to accelerate renewable energy deployment while maintaining economic stability, providing a transferable template for other developing economies pursuing rapid clean energy transitions.

The theoretical innovations presented here extend beyond immediate policy applications to establish new research frontiers at the intersection of behavioral economics, complex systems theory, and energy market design. The identification of evolutionary tipping points where carbon pricing triggers irreversible shifts toward low-carbon equilibria offers profound implications for climate policy timing and sequencing globally. Furthermore, our integration of multi-agent strategic interactions with real-time market dynamics opens pathways for developing intelligent energy systems that can adapt continuously to technological innovations, policy changes, and environmental uncertainties.

Looking toward the future, the methodological advances demonstrated through this research suggest transformative possibilities for energy system governance in an era of accelerating technological change and climate urgency. The EGT framework provides essential tools for understanding how artificial intelligence, blockchain technologies, and distributed energy resources will reshape competitive dynamics and strategic behaviors in ways that static analytical approaches cannot capture. As energy systems worldwide undergo fundamental structural transformations, the insights generated through this comprehensive analysis offer both theoretical foundations and practical guidance for ensuring that market evolution serves broader societal objectives of sustainability, equity, and resilience in the global transition toward carbon neutrality.

Glossary of Key Technical Abbreviations and Acronyms

This comprehensive glossary provides essential technical definitions for understanding the interdisciplinary nature of evolutionary game theory applications in sustainable energy systems. The selected abbreviations represent the most frequently utilized terms spanning game theory concepts, energy market mechanisms, carbon pricing instruments, and measurement units that form the analytical foundation of this research, enabling readers to navigate the complex interactions between theoretical frameworks and practical energy market applications.

Abbreviation	Definition and Application in This Study
AI (Artificial Intelligence)	Machine learning and computational intelligence technologies integrated with evolutionary game theory frameworks to enhance predictive capabilities and strategic decision-making processes in energy market optimization and demand response modeling.
CNY (Chinese Yuan)	China's national currency used throughout the study for carbon pricing, electricity pricing, and cost analysis, with carbon prices ranging from 20–100 CNY/tCO_2 and electricity prices around 400 CNY/MWh in simulation scenarios.

CO_2 (Carbon Dioxide)	Primary greenhouse gas measured in emissions trading systems, with emission factors of 0.8 tCO_2/MWh for coal-fired generation and zero for renewable sources, central to carbon pricing mechanism analysis and environmental impact assessment.
EGT (Evolutionary Game Theory)	Core theoretical framework analyzing strategic interactions among energy market participants through replicator dynamics, bounded rationality assumptions, and evolutionarily stable strategies to model long-term market behavior adaptation under carbon constraints.
EM (Electricity Market)	Competitive marketplace for electricity trading where generators submit bids and system operators clear markets, analyzed through evolutionary game dynamics to understand strategic bidding behavior evolution under carbon pricing mechanisms.
ESS (Evolutionarily Stable Strategy)	Equilibrium concept representing strategy distributions that cannot be invaded by alternative strategies, used to identify stable long-term configurations in energy market competition under varying carbon pricing scenarios.
ETS (Emissions Trading System)	Market-based carbon pricing mechanism establishing emission caps and tradeable allowances, with the EU ETS serving as primary comparative reference for analyzing China's national carbon trading system implementation and optimization.
GW (Gigawatt)	Unit of electrical power capacity measurement (10^9 watts) used to quantify generation capacity, renewable energy installations, and cross-regional transmission capabilities in China's electricity system transformation analysis.
HHI (Herfindahl-Hirschman Index)	Market concentration measure ranging from highly concentrated (>2500) to moderately concentrated (<1500), used to analyze the relationship between renewable energy penetration and competitive market structure evolution.
IEA (International Energy Agency)	Global energy policy organization providing authoritative data on renewable capacity expansion, energy transition trajectories, and carbon pricing mechanisms referenced throughout the comparative international analysis framework.
MCP (Marginal Cost Pricing)	Market clearing mechanism where electricity prices equal the marginal cost of the last dispatched generator, analyzed for interactions with carbon pricing and strategic bidding behavior evolution in competitive energy markets.
PAB (Pay-as-Bid)	Alternative pricing mechanism where generators receive their submitted bid prices rather than uniform market clearing prices, compared with MCP for analyzing differential impacts on carbon pricing transmission and market efficiency.
TWh (Terawatt-hour)	Unit of electrical energy measurement (10^{12} watt-hours) used to quantify electricity generation, cross-regional trading volumes, and renewable energy market penetration rates in China's evolving electricity system.
VPP (Virtual Power Plant)	Aggregated distributed energy resources managed through intelligent systems for optimal market participation, representing emerging technology paradigms requiring evolutionary game theory analysis for strategic coordination and profit optimization.

Author Contributions

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Not applicable.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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