frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 06 January 2025
DOI 10.3389/fenvs.2024.1491608

OPEN ACCESS

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RECEIVED 05 September 2024
ACCEPTED 11 November 2024
PUBLISHED 06 January 2025

CITATION
Xinfa T, Shuai L, Yonghua W, Youwei W and Dirane Nubea M (2025) Carbon emission reduction in China's iron and steel industry through technological innovation: a quadrilateral evolutionary game analysis under government subsidies.
Front. Environ. Sci. 12:1491608.
doi: 10.3389/fenvs.2024.1491608

Carbon emission reduction in China's iron and steel industry through technological innovation: a quadrilateral evolutionary game analysis under government subsidies

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The steel industry is notable for its significant environmental impact, highlighting the pressing need to promote technological innovation within the sector in order to reduce carbon emissions. This paper utilizes a quadrilateral evolutionary game model to analyze the strategic behaviors of steel producers, construction companies, scrap steel recyclers, and the government throughout the entire steel production, consumption, and recycling processes and their impact on carbon emission reduction. The analysis and simulation of the model provide policy insights for these four key players. The study's findings are as follows: (i) Government subsidies can effectively stimulate low-carbon production methods and encourage green consumer behavior. (ii) The strategic choices for technological innovation by steel manufacturers and scrap steel recyclers are primarily influenced by cost factors. Government subsidies for technological innovation play a crucial role in incentivizing a smooth transition to low-carbon production methods. (iii) For steel manufacturers, the carbon benefits derived from technological innovation are a critical factor influencing their engagement in such initiatives. If these manufacturers can benefit from environmental regulations, they are more likely to engage in technological innovation. (iv) The strategies of construction companies are influenced by production costs and carbon benefits associated with steel manufacturers, exhibiting threshold effects.

KEYWORDS

iron and steel industry, dual-carbon goals, technological innovation, evolutionary game, subsidize

1 Introduction

In the context of global low-carbon development, addressing the ongoing environmental degradation is a significant challenge encountered by nations worldwide. In September 2020, China explicitly introduced the "dual-carbon" goals as a long-term strategy for reducing greenhouse gas emissions in the 21st century (Hao et al., 2022), showcasing China's strong commitment to actively combatting climate change, embracing green and low-carbon development pathways, and fostering the collective advancement of humanity. As a pivotal industry with considerable potential for reducing carbon emissions, the iron and steel sector accounts for 5% of the world's total energy consumption and contributes 6% of global anthropogenic CO_2 emissions (Zhao et al., 2020). By 2021, China's iron and steel industry is projected to represent approximately 16% of the nation's overall carbon emissions, posing significant challenges to high-quality economic and social progress (Xu et al., 2022). Carbon emissions in the iron and steel production process primarily originate from fossil fuel combustion and chemical reactions during ironmaking, highlighting the pressing need for technological innovation in the sector to facilitate a transition towards low-carbon practices, a critical contemporary issue facing China.

Technological innovation stands as a pivotal strategy for the reduction of carbon emissions, offering the potential for significant cuts in CO_2 output through the integration of sophisticated production methodologies and the adoption of cleaner manufacturing technologies. In light of the imperative to address contemporary climate change, the urgency is heightened for the development of transformative CO_2 emission reduction technologies. Notably, the advancement of energy-saving technologies emerges as a paramount initiative in the quest for achieving carbon neutrality within the iron and steel sector (Wang et al., 2022). The enhancement of low-carbon technology innovation and its practical application is crucial for the iron and steel industry to meet its carbon reduction benchmarks. Scholars have illustrated that the expansion and utilization of high-temperature waste heat recovery technologies, coupled with the amalgamation of carbon capture and storage (CCS) methodologies, present a viable approach to diminishing CO_2 emissions attributable to iron and steel manufacturing processes (Paltsev et al., 2021). Concurrently, the enhancement of energy efficiency and the optimization of industrial processes constitute an efficacious route for carbon reduction. This approach is capable of yielding substantial decreases in both energy usage and carbon emissions, attributable to systemic energy conservation and the refinement of operational procedures (Sundaramoorthy et al., 2023; Tang et al., 2024). Energy consumption within the iron and steel production sector is primarily concentrated in pivotal processes like blast furnace ironmaking, converter steelmaking, and steel rolling. Coke, serving as the principal raw material for blast furnace ironmaking, stands as the largest fossil fuel directly utilized by the iron and steel industry. The exploration and utilization of alternative fuels, such as hydrogen replacing conventional carbon-based fuels, present a promising avenue for reducing carbon dioxide (CO_2) emissions during the iron and steel production process (Liu et al., 2021; Tang et al., 2020). Given hydrogen's role as a reducing agent with iron ore, yielding water instead of carbon dioxide, it underscores the significance of hydrometallurgy as a clean and revolutionary technology in steel production.

As the world's largest producer of steel, China accounts for half of the global output (Zhou and Yang, 2016). Within downstream industries, the construction sector remains the largest consumer of steel, representing 58.6% of direct steel consumption in China (Yang et al., 2023). This demand has remained stable, particularly as infrastructure development and urbanization progress are accelerated. However, regulatory policies in the real estate market in recent years have had a certain impact on the demand for construction steel (Yu et al., 2017). With the increasing demand from downstream industries for high-performance, eco-friendly steel materials, it is imperative for steel enterprises to intensify technological innovation and product upgrades. To address the various challenges of environmental pollution, both the steel industry and the construction sector are working together to promote the efficient use and recycling of steel materials through technological innovation and material development.

Achieving carbon emission reduction in the steel industry can be pursued through multiple avenues. The development of a circular economy, which enhances the recycling and utilization of scrap steel and thereby reduces the demand for new iron ore, constitutes an effective means of carbon emission reduction (Companero et al., 2021; Wuebbeke and Heroth, 2014). Driven by the momentum of scrap steel depreciation, there is a projected significant increase in the availability of scrap steel resources and the proportion of scrap steel used in the future (Xin et al., 2023). The construction sector generates a substantial amount of waste steel materials during demolition, maintenance, and construction processes. The recycling and utilization of this waste steel not only conserve iron ore resources and mitigate environmental degradation but also significantly reduce energy consumption and greenhouse gas emissions. Moreover, processed construction scrap steel can be repurposed as recycled steel materials in various sectors, including construction, transportation, and mechanical manufacturing, offering high recycling value. Currently, the scrap steel recycling and processing industry primarily employs advanced sorting technologies, sophisticated shredding techniques, and environmentally friendly treatment methods to achieve carbon emission reductions during the scrap steel processing. However, the application and promotion of these technologies face challenges related to technological maturity, economic costs, policy support, and market acceptance. A well-considered policy can offer substantial support for government regulation (Xu et al., 2024a). Consequently, boosting investment in technological innovation and enhancing policy incentives play a pivotal role in fostering technological innovation and mitigating carbon emissions across the entire iron and steel industry (Rissman, J. et al., 2020).

Carbon emission reduction in the steel industry involves numerous stakeholders, including downstream steel enterprises, scrap steel recyclers, and the government. Companies play a central role in the development of a low-carbon economy (Chang and Lo, 2022), and to encourage active corporate participation in low-carbon transitions, governmental policy support and stringent environmental regulation are essential. Governments worldwide have been implementing regulations and policies to mitigate climate change, aimed at fostering technological innovation for sustainable development (Dhayal et al., 2023). However, the enforcement of environmental policies often incurs substantial costs. To reduce the expenditure on environmental protection and management, governments increasingly rely on regulatory measures such as carbon taxes and subsidies to promote the widespread adoption of low-carbon technologies. To mitigate the environmental effects of pollutants, the government could enforce stringent regulations (Xu et al., 2024b). Some scholars argue that carbon taxes and subsidies positively influence manufacturers' adoption of low-carbon strategies (Chen et al., 2022; Yang and Nie, 2022). Additionally, a well-constructed regulatory framework can effectively stimulate innovation and enhance productivity (Ahmed, 2020). Furthermore, subsidies for low-carbon consumption by the government can stimulate market demand, thereby driving green production on the supply side (Ma et al., 2021). The incentives for green product consumption implemented by governments, coupled with consumers' growing positive attitudes towards these products, form the main driving force behind the growth of green product consumption (Hong et al., 2021). From the perspective of guiding social behavior, these subsidy policies not only offer economic rewards but, more importantly, they motivate economic actors to take proactive actions, thus promoting a harmonious coexistence between sustained economic growth and ecological and social wellbeing.

Currently, research on carbon emission reduction in the steel industry is quite extensive; however, most studies have focused on individual aspects, with few considering the integrated approach of production, consumption, and recycling. There is a scarcity of in-depth exploration into the interplay of strategies among different participants and the underlying mechanisms. This study zeroes in on four key players: steel manufacturers, construction companies, scrap steel recyclers, and the government. It examines the behavioral patterns and interactions among these parties under the incentive of government subsidies, aiming to provide practical guidance for technological innovation and carbon emission reduction in the steel industry. Nevertheless, achieving the optimal strategy selection and an ideal state for all parties involves a prolonged process of adjustment. By employing an evolutionary game model, this study aims to reveal the optimal strategies that each party should adopt to maximize the overall benefit of carbon emission reduction in the steel industry, thereby achieving a win-win outcome for technological advancement and environmental protection.

Therefore, this paper proposes a four-party evolutionary game model to investigate the following issues: (1) What are the strategic choices of stakeholders under the current state of insufficient technological innovation incentives in the steel industry, specifically in response to government subsidies for technological innovation and consumer subsidies? (2) What are the main factors influencing technological innovation in the steel industry? (3) How do the strategies of the parties in the game system influence each other? By addressing these questions, this paper aims to offer more flexible policy recommendations for the steel industry to achieve carbon emission reduction. The establishment of a multi-party evolutionary game model can reveal the true reactions of each participant in greater detail, better balance the interests of all parties, and on this basis, the paper attempts to provide practical and feasible suggestions for all stakeholders to promote the low-carbon development of the entire steel production, consumption, and recycling system. Additionally, this paper expands the application of evolutionary game theory by selecting four game entities to construct the model, providing a new perspective for future research on carbon emission issues in the steel industry using evolutionary game theory.

The remainder of this paper is structured as follows: In Chapter 2, a review and in-depth analysis of the relevant literature are conducted to demonstrate the innovation and practicality of this study. In Chapter 3, the research problem of this paper is described, and model assumptions are proposed. In Chapter 4, a stability analysis of the evolutionary game model is conducted, deriving the equilibrium conditions for system stability. Chapter 5 involves the valuation of the model and a sensitivity analysis to study the evolutionary trends of the parties in the system. In Chapter 6, the research findings are discussed, and policy implications for all stakeholders are presented. The final chapter summarizes the entire paper.

2 Literature review

The structure of this chapter is as follows: The initial section offers a comprehensive overview of the literature concerning the impact of technological innovation on carbon emissions, emphasizing the key role of innovation in steering the steel industry towards sustainability. The second section scrutinizes the multifaceted roles of stakeholders, including steel manufacturers, consumers, and policymakers, in the collective endeavor to reduce carbon emissions. The third section delves into the application of game-theoretic models, particularly evolutionary game theory, to analyze strategic interactions among stakeholders concerning carbon emissions. This section also discusses the novelty and potential contributions of the chosen model to the existing body of research.

2.1 Impact of technological innovation

The persistent global climate crisis has driven numerous countries to establish a comprehensive set of targets aimed at tackling and diminishing carbon emissions and a variety of other greenhouse gases. These targets can be effectively met by embracing and implementing technological innovations. Within the industrial sector, in particular, the role of technological innovation stands out as a potent force in reducing carbon emissions (Xu W. et al., 2023). With the ongoing expansion of the global economy and the heightened consciousness regarding environmental conservation, low-carbon manufacturing has progressively emerged as the prevailing trend in the evolution of new industries. It is widely acknowledged as a crucial pathway to attaining sustainable economic growth (Xiao et al., 2024). Low-carbon manufacturing is significantly driven by advancements in green technologies, which help to reduce carbon emissions during the production process by improving energy efficiency and adopting clean energy sources (Li et al., 2023). To address climate change and promote the transformation of the economy towards low-carbon development, it is crucial to encourage enterprises to adopt innovations in green and low-carbon technologies. Moreover, technological innovation must be achieved through appropriate low-carbon regulation to realize energy saving and emission reduction. The green technological innovation of enterprises is to some extent constrained by low-carbon regulatory policies, while also stimulating the role of these policies in enhancing green efficiency (Ding and Hu, 2022). An economic development model centered on green technological innovation is a key pathway to achieving the low-carbon transformation of the economy (Xu Y. et al., 2023). However, competition among local governments may suppress the positive effects of economic low-carbon transformation and green technological innovation. To foster innovation and application of low-carbon technologies, some scholars have proposed that, due to the limitations of research and development capabilities within a single industry, collaborative innovation involving industry, academia, research, and government (IURG) has become the most feasible solution for low-carbon technological innovation (Cui et al., 2020). Furthermore, several scholars have elucidated the intricate web of causality linking Foreign Direct Investment (FDI), green innovation, and CO2 emissions. Their findings offer crucial policy insights, guiding countries and regions on how to attain environmental sustainability through the lens of green innovation (Ali et al., 2022).

The low-carbon development of China's steel industry can be achieved through four key actions: improving energy efficiency, shifting towards scrap steel or electric arc furnace routes, advancing material efficiency strategies, and deploying incentive-based innovative technologies (Lin et al., 2021). Low-carbon innovative technologies and revolutionary innovations are crucial for carbon emission reduction, significantly impacting low-carbon development by reducing CO_2 emissions. Consequently, the government can stimulate the development of low-carbon technologies by formulating new policies and regulations related to the carbon market, thereby timely influencing the relationship between the carbon market and its participants (Sun et al., 2020). Although technological innovation is an effective way to address carbon emissions, different types of technological innovation may lead to varying environmental performance, and low-carbon technological innovation is key to achieving green production (Shi et al., 2021). Some scholars have found that energy consumption plays a significant mediating role in the impact of technological innovation on carbon emission reduction. The influence of technological innovation on carbon emissions is constrained by the level of energy consumption; low energy consumption significantly promotes the reduction of carbon emissions through technological innovation. However, once energy consumption exceeds a critical level, the facilitative effect of technological innovation on carbon emission reduction can turn into a suppressive one (Zhang et al., 2020). Additionally, other scholars have pointed out that digital technologies indirectly affect carbon emissions by influencing industry structure, technological innovation, and tax structure (Zeng and Yang, 2023; Lin and Ma, 2022).

The escalation of carbon emissions has accelerated low-carbon innovation in cities, with the type of low-carbon innovation exerting varying effects on its outcomes. Environmental awareness acts as an intermediary channel through which carbon emissions influence low-carbon innovation. With the assistance of media, government, and businesses, the growing volume of carbon emissions has heightened public environmental consciousness, altered consumer behavior, and spurred enterprises to quicken their pace of low-carbon innovation (Pan et al., 2021). Some scholars have also noted that the application of artificial intelligence technology has a positive impact on carbon reduction, where green technological innovation, green management innovation, and green product innovation play a moderating role, and corporate green innovation strengthens the impact of artificial intelligence on carbon reduction (Chen and Jin, 2023). Furthermore, government environmental regulation can effectively enhance corporate green innovation, with environmental investment serving as an intermediary. However, the development of environmental regulation in China is relatively lagging, and its positive incentive role remains to be further leveraged (Chen et al., 2023).

In summary, technological innovation plays a crucial role in promoting low-carbon manufacturing and sustainable economic development. Measures such as green technological innovation, inter-departmental collaboration, policy support, and raising environmental awareness can effectively facilitate industrial carbon reduction and achieve a green economic transition. How to achieve the low-carbon transformation of the socio-economic system through technological innovation is an important practical issue. At the same time, considering regional heterogeneity, governments need to formulate and implement region-specific technological innovation strategies for a certain period to promote global carbon reduction efforts.

2.2 Role of stakeholders in carbon emission reduction

The steel industry, as one of the primary sources of carbon emissions, is increasingly important in achieving carbon reduction targets (Wang and Lin, 2016). Steel manufacturers, as the main producers of steel products, directly impact the carbon footprint of the entire steel industry. It is estimated that the CO_2 emission intensity of the steel industry is 2.33 tons (CO_2/ton), with the production and manufacturing phase being the primary source of CO_2 emissions, accounting for 89.84% of the total emissions in the steel's entire lifecycle (Song et al., 2025). Under the current strategic goals of peak carbon and carbon neutrality, actively promoting energy-saving and low-carbon technologies and increasing the ratio of scrap steel to steelmaking aligns with the requirements of high-quality economic development. In traditional steel production processes, especially the blast furnace ironmaking method, high energy consumption and carbon emissions are significant (He et al., 2017). Therefore, manufacturers have tremendous potential and responsibility in technological innovation and optimization of the production process (Fu et al., 2014). For instance, they can optimize production processes to reduce the energy consumption and carbon emissions per unit of steel products by increasing the blast furnace pellet ratio and the electric furnace scrap rate (Na et al., 2024). They can also adopt advanced steelmaking technologies, utilizing green, pollution-free hydrogen energy, and using hydrogen plasma to reduce iron ore, thereby reducing CO_2 emissions at the source (Gajdzik et al., 2023). In addition, steel manufacturers can employ technologies such as Direct Reduced Iron (DRI) to achieve carbon reduction, thus producing low-carbon, green steel products (Nduagu et al., 2022; Sharifi and Barati, 2010).

Construction companies, as major consumers of steel products (Kanyilmaz et al., 2023), have a profound impact on the carbon reduction of the entire industry through their material selection preferences. In the construction industry, material choices not only affect the quality and cost of buildings but also directly relate to their environmental impact, particularly carbon emissions (Xu et al., 2020). With the growing global concern over climate change, an increasing number of construction companies are focusing on steel manufacturers that employ low-carbon production technologies to reduce the carbon footprint of their construction projects (Chen et al., 2018). Initially, construction companies often consider suppliers' environmental and carbon reduction policies when selecting material suppliers. Steel manufacturers committed to reducing carbon emissions typically adopt advanced production technologies and eco-friendly processes to decrease energy consumption and carbon emissions during production. These companies often highlight their environmental philosophies and carbon reduction measures in their promotional materials to attract construction companies with stronger environmental awareness. Subsequently, the construction industry is also actively exploring how to reduce steel material waste through technical means, thereby reducing carbon emissions (Nadoushani et al., 2018). Steel waste during construction is a serious issue in the construction industry, which not only increases project costs but also adversely affects the environment. Therefore, construction companies should not only focus on optimizing construction technology to reduce steel waste but also establish connections with recyclers to promote the recycling and reuse of scrap steel, as construction scrap steel indeed has significant potential value and environmental benefits (Czarnecki and Rudner, 2023).

Scrap steel recyclers play a crucial role in promoting the circular economy of the steel industry (Hu et al., 2020). In the production and consumption processes of steel, scrap steel, as a renewable resource, significantly contributes to reducing reliance on raw iron ore, saving energy, and lowering environmental pollution (Xuan and Yue, 2017). It is estimated that using scrap steel as raw material instead of iron ore to produce new steel can save a substantial amount of energy and reduce carbon emissions. Recycling 1 kg of scrap steel can reduce 1.5 kg of CO_2 equivalent emissions, 13.4 MJ of primary energy, and 1.4 kg of iron ore (Broadbent, 2016). Moreover, scrap steel recyclers improve the quality and efficiency of scrap steel recycling by employing advanced sorting and processing technologies, including magnetic separation, crushing, cleaning, and packaging technologies (Rem et al., 2012; Ferreira Neto et al., 2021), ensuring the purity and consistency of scrap steel materials to meet the requirements of steelmaking processes. However, the efficiency of scrap steel recycling and utilization is influenced by various factors. For example, the construction of recycling channels (Berlin et al., 2022; Gu et al., 2021), scrap steel classification standards (Gao et al., 2023; Xu D. et al., 2023), market demand (Watari et al., 2023), and policy support all affect the recycling and utilization of scrap steel. Therefore, the government and the industry need to work together to improve the recycling rate of scrap steel through reasonable policies, financial support, strengthening technological research and development, and enhancing environmental awareness.

To promote the achievement of carbon reduction targets, the government can formulate clear carbon reduction targets (Bai et al., 2023), provide tax incentives (Tang et al., 2021), and R&D subsidies to encourage enterprises to reduce pollution and carbon emissions (Qi et al., 2023). For consumers, green consumption subsidies and green product certification are also effective ways to motivate green consumption behavior (Yang et al., 2022). Government regulation of firms, facilitated by the strategic implementation of subsidies, effectively enhances economic efficiency while simultaneously promoting environmental sustainability (Chen et al., 2024). Carbon reduction in the steel industry is a systematic project involving multiple industries and links. Steel manufacturers, construction companies, and scrap steel recyclers must work together to achieve carbon reduction through technological innovation and optimized management. At the same time, government policy support and the improvement of the market mechanism are also indispensable. Therefore, steel manufacturers, construction companies, and scrap steel recyclers each play different but interconnected roles, jointly promoting the development of the entire industry towards a lower-carbon and more sustainable direction. It is essential for industry players to leverage innovation and foster collaboration in order to mitigate risks and enhance their own development by capitalizing on the opportunities presented by the emerging market trends (Xiao and Xu, 2024). This paper will analyze these roles in detail and discuss how to more effectively achieve carbon reduction in the steel industry under government subsidies.

2.3 Applications of game theory

Game theory studies the decision-making processes of participants whose actions are interconnected and mutually influential, an analytical framework that has been widely applied across various fields (Eissa et al., 2021; Kaplinski and Tamosaitiene, 2010; Moretti and Vasilakos, 2010). Evolutionary game theory, a further development of game theory, is utilized to analyze and predict the strategic choices and evolutionary processes of individuals in long-term interactions (Estalaki et al., 2015).

Many scholars have conducted extensive research on carbon emission issues across various fields using game theory. To effectively understand the collaborative evolution mechanism among three stakeholders in carbon trading—government, emission reduction enterprises, and carbon control enterprises—Hu and Wang (2023) analyzed the selection mechanism of carbon trading participants' game strategies through repeated dynamic equations and discussed the main factors affecting the evolution and stable outcomes of carbon trading through scenario simulation. Liu et al. (2022) constructed an evolutionary game model for local government cooperation in emission reduction, finding that the likelihood of the government choosing a cooperative emission reduction strategy increases at different rates based on the benefits and costs of cooperation. Additionally, carbon tax policies affect the likelihood of local governments choosing cooperative emission reduction, with different carbon tax scales having varying impacts on their willingness to cooperate. Cui et al. (2022) built a trilateral game model between enterprises and the government, concluding that carbon prices, additional green technology innovation benefits, and innovation incentives significantly impact corporate strategic choices, with different strategic selections made by enterprises with varying innovation input-output ratios under the same conditions. Li et al. (2022) simulated the evolutionary game path of government and corporate carbon reduction under the "Dual carbon" goals using carbon market transaction data, finding that increasing financial subsidies can improve the probability of high-pollution enterprises reducing carbon emissions, and intensifying carbon emission penalties helps high-pollution enterprises actively reduce emissions. Zhao and Liu (2019) established an evolutionary game framework between the government and enterprises to study the adoption of carbon capture and storage (CCS) technology from a micro perspective, which is significant for policy support, low-carbon power generation revenue, and reducing the cost of CCS adoption for power companies. To encourage enterprises to reduce carbon emissions, Li et al. (2024) constructed a three-party evolutionary game model to explore the interactive behavior between the government, enterprises, and customers, concluding that to encourage enterprises to reduce carbon emissions, it is necessary to guide customers to purchase low-carbon products. Moreover, customers are more sensitive to low-carbon consumption subsidies than to consumption taxes. Xue et al. (2022) studied the dynamic decision-making process of three stakeholders—manufacturing enterprises, government regulatory departments, and media investigation institutions—regarding stable strategies based on evolutionary game theory. The main factors affecting the stable strategies of the three stakeholders were identified as income, subsidies, costs, and losses.

In the steel industry, Liu et al. (2023) established a three-party evolutionary game model between steel enterprises, scrap steel enterprises, and the government and conducted simulation analysis, deriving three evolutionary stable strategies for the formation of scrap steel bases and determining that the optimal strategy is with the participation of steel and scrap steel enterprises and minimal government intervention. This provides unique insights and theoretical support for promoting the development of the scrap steel industry and helping to achieve peak carbon and carbon neutrality strategies. Duan et al. (2017) constructed a two-stage dynamic game model for China's steel industry, incorporating factors such as carbon tax collection, product subsidies, and carbon capture and storage (CCS) into the emission reduction mechanism, studying the overall emission reduction effects and economic impact of the steel industry. Li et al. (2022) constructed a repeated dynamic game model that includes carbon trading policies and other mixed emission reduction policies, proposing that enterprises should comprehensively consider factors such as emission reduction policies, output adjustment policies, and carbon trading benchmarks to ensure that enterprises and the entire market do not fall into an unbalanced state. Zhang and Zhang (2022) established an evolutionary game model between steel enterprises under the government subsidy mechanism and introduced a carbon quota trading mechanism to determine the optimal collaborative atmospheric pollution management strategy between large and small steel enterprises under government subsidy policies. It was found that government subsidies and the input-output ratio are crucial for enterprises to cooperate in atmospheric pollution control investment, providing unique insights and theoretical support for steel enterprises to achieve carbon reduction.

According to existing research, although game theory has been widely used to analyze the impact of carbon emission policies in the steel industry, these studies have mostly focused on the interactions between the government and steel manufacturers, which are bilateral or trilateral. However, the steel industry is a complex system with multiple stakeholders, and current government subsidy policies tend to favor manufacturers and consumers, neglecting scrap steel recyclers who have significant potential for carbon reduction. This study expands the perspective to the entire steel industry, incorporating steel manufacturers, construction companies, scrap steel recyclers, and the government into an integrated system, to comprehensively analyze the coordinated dynamics and evolutionary trends of all parties in carbon reduction efforts. Through this multidimensional analytical framework, this study aims to reveal how different stakeholders interact, thereby providing a deeper insight into the green transformation of the steel industry. In the research of this paper, traditional game theory is not applicable because it is based on the assumption that participants have complete rationality and can obtain complete information. Obviously, such assumptions are unrealistic for the participants in this study. Enterprises and governments cannot fully grasp each other's needs and specific situations. In contrast, Evolutionary Game Theory (EGT) provides a more realistic analytical framework, assuming that participants have limited rationality and are in an environment of asymmetric information (Wang et al., 2021). This theory is closer to reality and can better explain and predict the participants' strategic choices and behavioral evolution under incomplete information.

3 Problem description and model assumptions

Through the introduction in Chapter 1 and the literature review in Chapter 2, we have gained an in-depth understanding of the current state of the steel industry and the issues related to carbon reduction. To better construct the model and draw innovative conclusions, the following sections will delve into the core issues of this study and provide a detailed introduction to the model's construction and the basis of its assumptions. This process will offer us a more comprehensive analytical framework to reveal the new mechanisms of carbon reduction technology innovation in the steel industry. The assumptions are as follows.

(1) This paper selects steelmaker, construction conpany, scrap recycler, and the government as the game players. The government, as an important player in the game, aims to promote technological innovation in steelmaker and scrap recycler through technological innovation subsidies; at the same time, it uses consumption subsidies to encourage green consumption by construction company. On the basis of maximizing the interests of all parties, the goal is to achieve carbon reduction targets in the production, consumption, and recycling processes of steel, promote the low-carbon transformation of the entire steel industry, and thus improve the level of sustainable environmental development. The strategies of the four parties are: the probability of steelmaker engaging in technological innovation is x, and the probability of not doing so is $1-x,\ x \in [0,1]$; the probability of construction company choosing green consumption is y, and the probability of choosing traditional consumption is $1-y,\ y \in [0,1]$; the probability of scrap recycler engaging in technological innovation is z, and the probability of not doing so is $1-z,\ z \in [0,1]$; the probability of the government

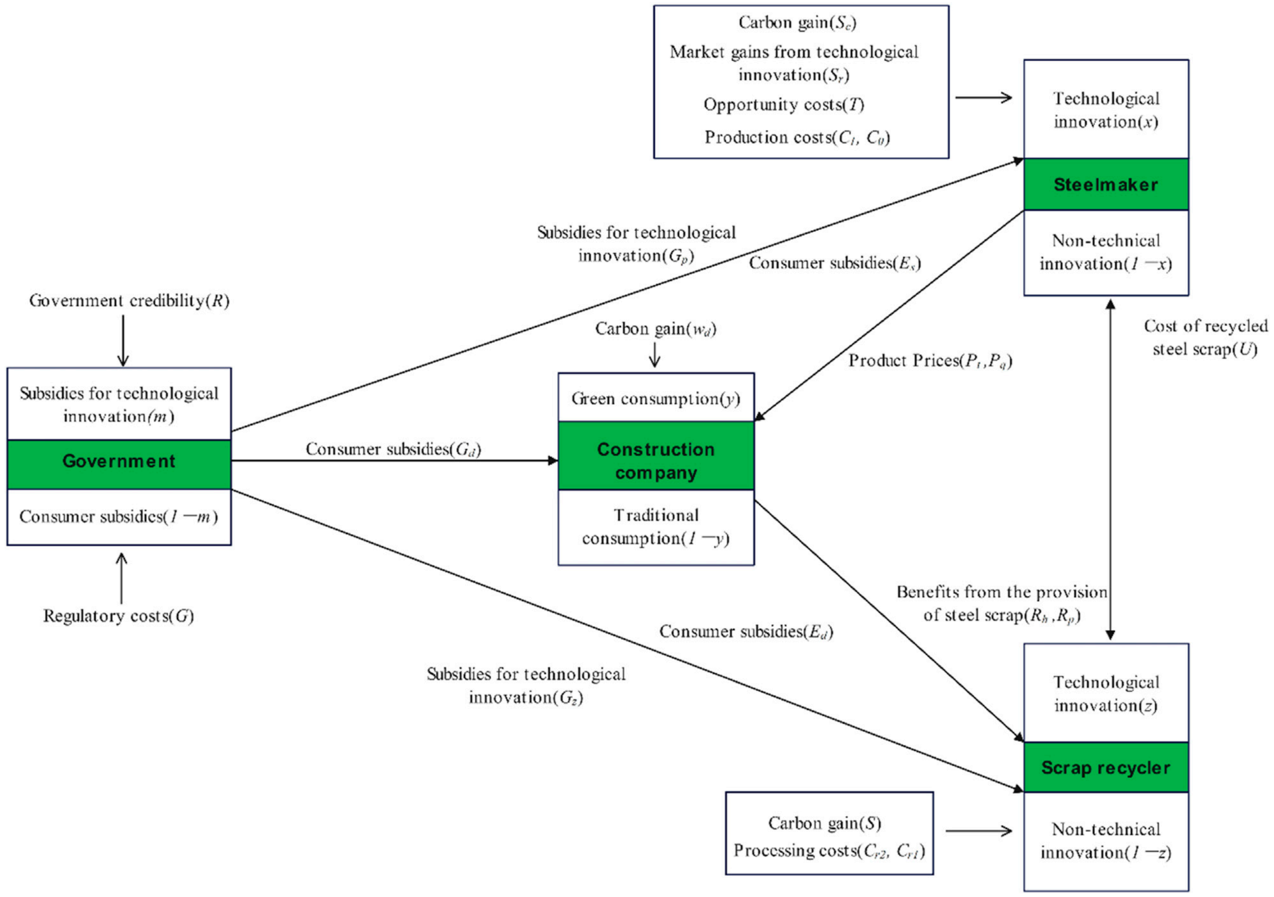

FIGURE 1
Evolutionary game modeling logics.

implementing technological innovation subsidies is m, and the probability of implementing consumption subsidies is $1-m$, $m \in [0,1]$. All four entities are assumed to be boundedly rational and continuously adjust their strategies over time to maximize their own interests.

(2) Assumptions for the strategies of steelmaker. Steelmaker that engage in technological innovation to produce green products will be favored by construction enterprises with stronger environmental awareness, thereby obtaining an additional market revenue S_r. At the same time, steel manufacturers after technological innovation can gain benefits S_c from environmental regulation (Wu et al., 2023). If steel manufacturers do not engage in technological innovation, they will also lose a certain amount of opportunity cost T. In addition, under the technological innovation production model of steel manufacturers, the production cost will increase significantly. This paper sets the unit production cost after technological innovation as C_1, and the original production cost as C_0, with $C_1 > C_0$. Considering that technological innovation by steel manufacturers will cause an increase in product prices, the unit price of green products is set as P_t, and the unit price of traditional products as P_q, with $P_t > P_q$. When steel manufacturers engage in technological innovation, if the government provides technological innovation subsidies, then the unit price of green products will be the same as that of traditional products, P_q. If the government does not subsidize the steel manufacturers, then the unit price of green products will be P_t.

(3) Assumptions for the strategies of construction company. When construction enterprises choose green products, they will receive a certain carbon benefit w_d. During the production process of green products, carbon reduction value is achieved, while traditional products only achieve use value and cannot realize carbon reduction (Muslemani et al., 2021). However, whether it is green or traditional products, construction enterprises can earn profits U by providing scrapped products to scrap steel recyclers. If construction enterprises want to purchase traditional products, but manufacturers only produce green products, it will lead to product unsellability. Consumers will give up purchasing due to the lack of suitable products, and scrap steel recyclers will not need to recycle. As a result, steel manufacturers will not profit from product sales, and the costs and revenues of construction enterprises and scrap steel recyclers will both be 0.

(4) Assumptions for the strategies of scrap recycler. Scrap steel recyclers engaging in technological innovation will obtain

certain carbon benefits S, but technological innovation will increase processing costs. This paper sets the processing cost of scrap steel recyclers after technological innovation as C_{r2}, and the original processing cost as C_{r1}, with $C_{r2} > C_{r1}$. Because scrap steel recyclers engaging in technological innovation often have greater benefits compared to not engaging in innovation, the price of scrap steel provided to steel manufacturers will also be higher than usual. Therefore, the prices of scrap steel provided to steel manufacturers before and after technological innovation by scrap steel recyclers are set as R_h and R_p, respectively, with $R_h > R_p$. The cost of scrap steel recyclers to recover scrap steel from construction enterprises is U, which is consistent with the revenue from construction enterprises providing scrap steel.

(5) Assumptions for the strategies of the government. The government incentivizes firms to curb emissions by allocating rational green funds, thereby prompting them to lower their emissions (Chen and Li, 2023). In the model, the government adopts two different forms of subsidies, namely, technological innovation subsidies or consumption subsidies. The government should bear the corresponding costs G in the process of regulatory management of the subsidy system. When the government provides consumption subsidies to all parties, steelmaker, construction company, and scrap recycler will have a deeper understanding of the government's work, thereby improving the government's credibility R. This paper sets the government's consumption subsidies to steel manufacturers, construction enterprises, and scrap steel recyclers as E_s, G_d, and E_d, respectively, and the government's technological innovation subsidies to steel manufacturers and scrap steel recyclers as G_p and G_z, respectively.

In summary, the game model relationship constructed in this paper is shown in Figure 1, the relevant model parameters are shown in Table 1, and the system's four-party game payoff matrix is shown in Table 2.

4 Evolutionary game analysis

Based on the replicator dynamics equations of steelmaker, construction company, scrap recycler, and the government, a series of solutions for the replicator dynamics equations of each party are derived, and the stability of the four-party evolutionary game is analyzed.

4.1 Stability analysis of strategies for steelmaker

Steelmakers' expected revenues under the innovative technological production model and the traditional production model are denoted as V_{11} and V_{12}, respectively, with the average expected revenue for both being V_1.

$$\begin{cases} V_{11} = S_c - C_1 + S_r + mG_p + yE_s + yP_t - yR_p - ymE_s + ymP_q - ymP_t \\ \qquad -yzR_{\mathrm{h}} + yzR_p \\ V_{12} = P_q - R_p - C_0 - T - yP_q + yR_p - zR_h + zR_p + yzR_h - yzR_p \\ V_1 = xV_{11} + (1-x)V_{12} \end{cases} \tag{1}$$

From Equation 1, we can derive the replicator dynamics equation for steel manufacturers, which is:

$$\begin{aligned} F(x) = \frac{dx}{dt} &= x(V_{11} - V_1) = x(1-x)(V_{11} - V_{12}) \\ &= x(1-x)(R_p - P_q + S_c - C_1 + C_0 \\ &\quad + S_r + T + mG_p + yE_s + yP_q + yP_t - 2yR_p + zR_h \\ &\quad - zR_p - ymE_s + ymP_q - ymP_t - 2yzR_h + 2yzR_p) \end{aligned}$$

Taking the first derivative of $F(x)$, then:

$$\begin{aligned} F'(x) = \frac{dF(x)}{dx} &= (1-2x)(V_{11} - V_{12}) \\ &= (1-2x)(R_p - P_q + S_c - C_1 + C_0 + S_r + T \\ &\quad + mG_p + yE_s + yP_q + yP_t - 2yR_p + zR_h \\ &\quad - zR_p - ymE_s + ymP_q - ymP_t - 2yzR_h + 2yzR_p) \end{aligned}$$

Based on the stability theorem of differential equations, the probability that the strategy of steelmaker is in a stable state must satisfy the following formula: $F(x) = 0$ and $F'(x) < 0$.

Proof 1. Let $G(y) = (R_p - P_q + S_c - C_1 + C_0 + S_r + T + mG_p + yE_s + yP_q + yP_t - 2yR_p + zR_h - zR_p - ymE_s + ymP_q - ymP_t - 2yzR_h + 2yzR_p)$, and then find the first-order derivatives of $G(y)$ to get $G'(y) = E_s + P_q + P_t - 2R_p - mE_s + mP_q - mP_t - 2zR_h + 2zR_p$, it is clear that $G'(y) > 0$, so $G(y)$ is a monotonically increasing function with respect to y. $G(y) = 0$ gives $y^* = -(R_p - P_q + S_c - C_1 + C_0 + S_r + T + mG_p + zR_h - zR_p)/(E_s + P_q + P_t - 2R_p - mE_s + mP_q - mP_t - 2zR_h + 2zR_p)$. If $y < y^*$, then it can be inferred that $G(y) < 0$, which leads to $F(x)|_{x=0} = 0$ and $F(x)|_{x=0} < 0$, which suggests that $x = 0$ is a stable strategy point for the evolution of steel manufacturers. If $y > y^*$, then it can be inferred that $G(y) > 0$, which leads to $F(x)|_{x=1} = 0$ and $F(x)|_{x=1} < 0$, which indicates that $x = 0$ is a stable strategy point for the evolution of the steelmaker. Otherwise, i.e., $y = y^*$, then $G(y) = 0$ and thus $F(x) = F'(x) = 0$. Therefore, the stable strategy for the evolution of the steelmaker cannot be determined.

Proof 2. $y^* = -(R_p - P_q + S_c - C_1 + C_0 + S_r + T + mG_p + zR_h - zR_p)/(E_s + P_q + P_t - 2R_p - mE_s + mP_q - mP_t - 2zR_h + 2zR_p)$, and the first-order partial derivatives of the variables of interest with respect to y^* give, $\frac{\partial y^*}{\partial z} < 0$, $\frac{\partial y^*}{\partial R_p} < 0$, $\frac{\partial y^*}{\partial P_q} < 0$, $\frac{\partial y^*}{\partial P_t} > 0$, $\frac{\partial y^*}{\partial S_c} > 0$, $\frac{\partial y^*}{\partial C_1} > 0$, $\frac{\partial y^*}{\partial C_0} < 0$, $\frac{\partial y^*}{\partial S_r} > 0$, $\frac{\partial y^*}{\partial T} < 0$, $\frac{\partial y^*}{\partial G_p} > 0$, $\frac{\partial y^*}{\partial R_h} < 0$, $\frac{\partial y^*}{\partial E_s} > 0$. Thus y^* is positively correlated with P_t, S_c, C_1, S_r, G_p, E_s and negatively correlated with z, R_p, P_q, C_0, T, R_h.

(1) From Proof 1, it can be deduced that as the likelihood of green consumption by construction companies increases, it will lead steel manufacturers to transition from traditional production models to technologically innovative production models. Therefore, for the government, it is imperative to implement relevant policies and incentives to encourage construction companies to purchase green products, thereby promoting the low-carbon transition of steel

TABLE 1 Model parameter setting.

Nomenclature	
S_r	Market gains from technological innovation for steelmaker
C_1, C_0	Production costs after technological innovation and original production costs for steelmaker $C_1 > C_0$
T	Lost opportunity costs for steelmakers not to innovate technologically
S_c	Carbon benefits of technological innovation for steelmaker
P_t	Prices of green products (when government does not subsidize technological innovation for steelmaker)
P_q	Price of conventional product (when the government subsidizes technological innovation for steelmaker, the price of the product after technological innovation is alsoP_t) $(P_q < P_t)$
w_d	Carbon gains from green consumption by construction company
U	Revenue from scrap supplied by construction company (cost of recycling scrap by scrap recycler)
R_h	Revenues from the provision of scrap by technologically innovative scrap recycler (cost of recovering scrap by steelmaker)
R_p	Revenues received by scrap recycler from the supply of steel scrap $(R_p < R_h)$
C_{r2}, C_{r1}	Processing costs after technological innovation by scrap recycler and original processing costs $C_{r2} > C_{r1}$
S	Carbon gains from technological innovation for scrap recycler
R	Government credibility (consumer subsidies lead to increased government credibility)
G_p	The cost of government subsidies for technological innovation for steelmaker
G_d	Costs of government consumption subsidies to construction company for purchasing green products
E_d	Cost of government consumption subsidies to scrap recycler for recycling scrap (when scrap recycler undertake technological innovations)
G_z	The cost of government subsidies for technological innovation for scrap recycler
E_s	Cost of government consumption subsidies to technologically innovative steelmaker
G	Regulatory costs arising from government subsidies

manufacturers. In addition, the main factors influencing the strategic choices of steel manufacturers include product prices, carbon benefits from technological innovation, production costs after technological innovation, opportunity costs, original production costs, market revenue from technological innovation, the cost of reclaiming scrap steel, technological innovation subsidies, and scrap steel consumption subsidies.

(2) According to the conclusion of Proof 1, when $(R_p - P_q + S_c - C_1 + C_0 + S_r + T + mG_p + yE_s + yP_q + yP_t - 2yR_p + zR_h - zR_p - ymE_s + ymP_q - ymP_t - 2yzR_h + 2yzR_p) > 0$, the evolutionary stabilization strategy of the steel manufacturer is to adopt a technologically innovative production model. Threshold $y^* = -(R_p - P_q + S_c - C_1 + C_0 + S_r + T + mG_p + zR_h - zR_p)/(E_s + P_q + P_t - 2R_p - mE_s + mP_q - mP_t - 2zR_h + 2zR_p)$, if $y < y^*$, the steel manufacturer's evolutionary stabilizing strategy is to adopt the traditional mode of production, and if $y > y^*$, the steel manufacturer's evolutionary stabilization strategy is to adopt a technologically innovative production model. Otherwise, the steel manufacturer's evolutionary stabilization strategy cannot be determined.

(3) Proof 2 shows that when steel manufacturers make technological innovations, they will bring certain market gains from technological innovations and carbon gains, and construction firms will be inclined to buy green products despite the increase in production costs and product prices. At the same time, if the government increases the subsidies for technological innovation for steel manufacturers and the consumption subsidies for steel scrap, construction companies will tend to buy green products, which will constitute a virtuous circle between low-carbon production and green consumption. In addition, the cost of steel manufacturers to recover scrap, the price of conventional products, the original production cost, and the lost opportunity cost will all contribute to the tendency of construction companies to purchase conventional products, which will ultimately affect the strategic choices of steel manufacturers to carry out technological innovation.

(4) The phase diagram chosen by the steelmaker's strategy is determined by the relevant parameters, specifically, by $y^* = -(R_p - P_q + S_c - C_1 + C_0 + S_r + T + mG_p + zR_h - zR_p)/(E_s + P_q + P_t - 2R_p - mE_s + mP_q - mP_t - 2zR_h + 2zR_p)$, which is given by the fact that when $y^* = 0$, $z_1 = -(R_p - P_q + S_c - C_1 + C_0 + S_r + T + mG_p)/(R_h - R_p)$, and when $y^* = 1$, $z_2 = (E_s + P_t - R_p + S_c - C_1 + C_0 + S_r + T + mG_p - mE_s + mP_q - mP_t)/(R_h - R_p)$, and since the sizes of z_1 and z_2 are indeterminable, it may be useful to set $0 < z_1 < z_2 < 1$. As shown in Figure 2 and Equation 2, D_{11} denotes the probability that the steel manufacturer adopts the strategy of technological innovation production mode, and D_{12}

TABLE 2 Payment matrix for the four-party game.

Strategy selection		Construction company		Government			
				Subsidies for technological innovation (*m*)		Consumer subsidies (1-*m*)	
			Scrap recyclers	Technological Innovations (*z*)	Non-technical innovation (1-*z*)	Technical innovation (*z*)	Non-technical innovation (1-*z*)
Steelmaker	Technical innovation (*x*)	Green consumption (*y*)		$S_r - C_1 + S_c + P_q - R_h + G_p$ $w_d + U - P_q$ $R_h - C_{r2} + S + G_z - U$ $-G_p - G_z - E_s - G$	$S_r - C_1 + S_c + P_q - R_p + G_p$ $w_d + U - P_q$ $R_h - C_{r1} - U$ $-G_p - E_s - G$	$S_r - C_1 + S_c + P_t - R_h + E_s$ $w_d + U + G_d - P_t$ $R_h - C_{r2} + S + E_d - U$ $R - G_d - E_d - E_s - G$	$S_r - C_1 + S_c + P_t - R_p + E_s$ $w_d + U + G_d - P_t$ $R_p - C_{r1} - U$ $R - G_d - E_s - G$
		Traditional consumption (1-*y*)		$S_r - C_1 + S_c + G_p$ 0 0 $-G_p - G_z - G$	$S_r - C_1 + S_c + G_p$ 0 0 $-G_p - G$	$S_r - C_1 + S_c$ 0 0 $-G_p - G$	$S_r - C_1 + S_c$ 0 0 $-G_p - G$
	Non-technical innovation (1-*x*)	Green consumption (*y*)		$-T - C_0$ 0 G_z $-G_z - G$	$-T - C_0$ 0 G_z $-G$	$-T - C_0$ 0 G_z $-G$	$-T - C_0$ 0 G_z $-G$
		Traditional consumption (1-*y*)		$-T - C_0 + P_q - R_h$ $U - P_q$ $R_h - C_{r2} + S + G_z - U$ $-G_z - G$	$-T - C_0 + P_q - R_P$ $U - P_q$ $R_P - C_{r1} - U$ $-G$	$-T - C_0 + P_q - R_h$ $U - P_q$ $R_h - C_{r2} + S + E_d - U$ $R - E_d - G$	$-T - C_0 + P_q - R_p$ $U - P_q$ $R_p - C_{r1} - U$ $R - G$

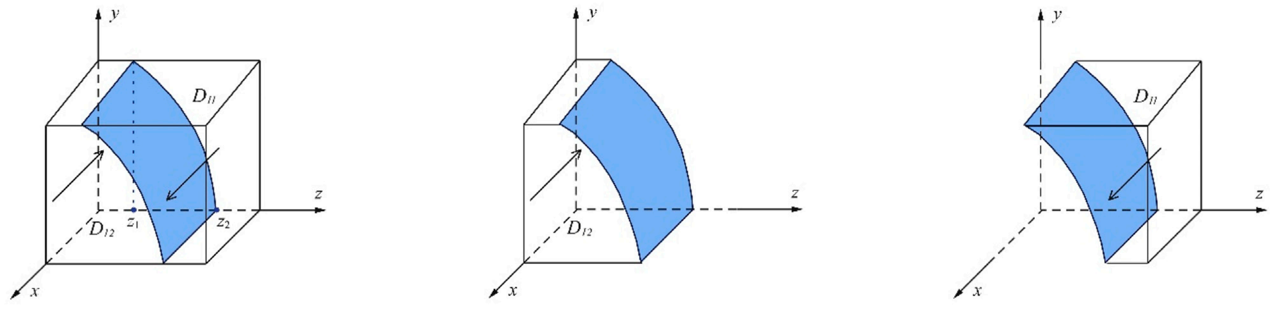

FIGURE 2
Phase diagram of strategic options for steelmaker.

denotes the probability that the steel manufacturer adopts the strategy of traditional production mode.

$$\begin{cases} D_{11} = 1 - D_{12} = 1 - \left(\int_0^1 \int_{z_1}^{z_2} y^* dxdz + \int_0^1 \int_0^{z_1} dxdz \right) \\ D_{12} = \int_0^1 \int_{z_1}^{z_2} y^* dxdz + \int_0^1 \int_0^{z_1} dxdz \end{cases} \tag{2}$$

4.2 Stability analysis of strategies for construction company

The expected revenues of construction company under green and traditional consumption are V_{21} and V_{22}, respectively, and the average expected revenue for both is V_2.

$$\begin{cases} V_{21} = x\left(w_d + U + G_d - P_t - mG_d - mP_q + mP_t\right) \\ V_{21} = (1-x)\left(U - P_q\right) \\ V_2 = yV_{21} + (1-y)V_{22} \end{cases} \tag{3}$$

From (Equation 3), the equation for the replication dynamics of construction company can be obtained as:

$$\begin{aligned} F(y) = \frac{dy}{dt} &= y(V_{21} - V_2) = y(1-y)(V_{21} - V_{22}) \\ &= y(1-y)\big(P_q - U + xw_d + 2xU + xG_d \\ &\quad -xP_q - xP_t - xmG_d - xmP_q + xmP_t) \end{aligned}$$

Taking the first derivative of $F(y)$, then:

$$\begin{aligned} F'(y) = \frac{dF(y)}{dy} &= (1-2y)(V_{21} - V_{22}) \\ &= (1-2y)\big(P_q - U + xw_d + 2xU + xG_d \\ &\quad -xP_q - xP_t - xmG_d - xmP_q + xmP_t) \end{aligned}$$

According to the stability theorem of differential equations, the probability that a construction firm's strategy is in a steady state must satisfy the following formulas: $F(y) = 0$ and $F'(y) < 0$.

Proof 3. Let $H(m) = (P_q - U + xw_d + 2xU + xG_d - xP_q - xP_t - xmG_d - xmP_q + xmP_t)$, and then find the first-order derivative of $H(m)$, we get $H'(m) = -x(G_d + P_q - P_t)$, obviously $H'(m) > 0$, so $H(m)$ is a monotonically increasing function with respect to m. When $H(m) = 0$, $m^* = (Pq - U + xWd + 2xU + xGd - xPq - xPt)/(xGd + xPq - xPt)$. If $m < m^*$,then it can be inferred that $H(m) < 0$, which leads to $F(y)|_{y=0} = 0$ and $F'(y)|_{y=0} < 0$, which suggests that $y = 0$ is the point of evolutionarily stable strategy for the construction firm. If $m > m^*$,then it can be inferred that $H(m) > 0$, which leads to $F(y)|_{y=1} = 0$ and $F'(y)|_{y=1} < 0$, which suggests that $y = 1$ is an evolutionarily stable strategy point for the construction firm. Otherwise, i.e., $m = m^*$, then $H(m) = 0$ and thus $F(y) = F'(y) = 0$. Therefore, the evolutionary stabilization strategy of the construction company cannot be determined.

Proof 4. $m^* = (Pq - U + xWd + 2xU + xGd - xPq - xPt)/(xGd + xPq - xPt)$, and taking the first-order partial derivatives of the variables of interest with respect to m^* yields that $\frac{\partial m^*}{\partial x} > 0$, $\frac{\partial m^*}{\partial P_t} < 0$, $\frac{\partial m^*}{\partial P_q} > 0$, $\frac{\partial m^*}{\partial w_d} < 0$, and $\frac{\partial m^*}{\partial G_d} < 0$, i.e., m^* is positively correlated with x, P_q is positively correlated and negatively correlated with P_t, w_d, G_d.

(1) Proof 3 indicates that as m evolves from 0 to 1, y also evolves from 0 to 1. This implies that as the government inclines towards implementing technological innovation subsidies, construction enterprises will tend to purchase green products. The key factors influencing the strategic choices of construction enterprises are the price of the products, the revenue from selling scrap steel, the government's consumption subsidies, and the carbon benefits derived from green consumption.

(2) According to Proof 3, when $(Pq - U + xWd + 2xU + xGd - xPq - xPt - xmGd - xmPq + xmPt) > 0$, the evolutionary stabilization strategy of construction company is green consumption, with the threshold $m^* = (Pq - U + xWd + 2xU + xGd - xPq - xPt)/(xGd + xPq - xPt)$. If $m < m^*$, the evolutionary stabilization strategy of the construction firm is conventional consumption; if $m > m^*$, the evolutionary stabilization strategy of the construction firm is green consumption. Otherwise, the evolutionary stabilization strategy of the construction firm cannot be determined.

(3) If the government focuses on implementing technological innovation subsidies, steel manufacturers will be attracted by the benefits of low-carbon production. Due to fierce competition, steel manufacturers will produce a large quantity of green products, leading to the phasing out of traditional products. Consequently, construction enterprises will be more inclined to purchase green products. Therefore, the government's technological innovation subsidies have a crucial impact on both steel manufacturers and construction

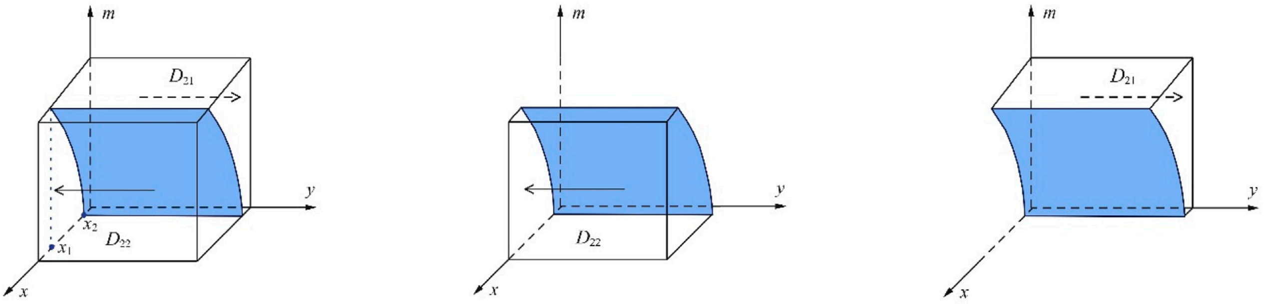

FIGURE 3
Phase diagram of strategic options for construction company.

enterprises, compelling steel manufacturers to engage in low-carbon production. According to Proof 4, in the short term, the government should primarily increase consumption subsidies to encourage construction enterprises to buy green products. At the same time, the government should regulate the market prices of green products to prevent construction enterprises from favoring the purchase of traditional products. This approach will enhance the carbon benefits derived from green consumption.

$$\begin{cases} D_{21} = 1 - D_{22} = 1 - \left(\int_0^1 \int_{x_2}^{x_1} m_\star dxdy + \int_0^1 \int_{x_1}^1 dxdy \right) \\ D_{22} = \int_0^1 \int_{x_2}^{x_1} m_\star dxdy + \int_0^1 \int_{x_1}^1 dxdy \end{cases} \tag{4}$$

(4) The phase diagram of the strategy choice of the construction enterprise is determined by the relevant parameters, specifically, by $m^\star = (Pq - U + xWd + 2xU + xGd - xPq - xPt)/(xGd + xPq - xPt)$, when $m^\star = 0$, $x_1 = (U - Pq)/\ (Wd + 2U + Gd - Pq - Pt)$, when $m^\star = 1$, $x_2 = (U - Pq)/\ (Wd + 2U - 2Pq)$, it is clear that $0 < x_2 < x_1 < 1$. As shown in Figure 3 and Equation 4, D_{21} denotes the probability of green consumption of construction firms, and D_{22} denotes the probability of traditional consumption of construction firms.

4.3 Stability analysis of strategies for scrap recycler

The expected revenues of scrap recyclers under technological and non-technological innovations are V_{31} and V_{32}, respectively, and the average expected revenue for both is V_3.

$$\begin{cases} V_{31} = m(x-1)(y-1)(G_z - U + S - C_{r2} + R_h) + xym(G_z - U + S - C_{r2} + R_h) \\ \qquad -xm(y-1)G_z - my(x-1)G_z - (m-1)(x-1)(y-1)(E_d - U + S - C_{r2} + R_h) \\ \qquad -xy(m-1)(E_d - U + S - C_{r2} + R_h) \\ V_{32} = (x + y - 2xy - 1)(U - R_p + C_{r1}) \\ V_3 = zV_{31} + (1-z)V_{32} \end{cases} \tag{5}$$

From (Equation 5), the equation for the replication dynamics of the scrap recycler can be obtained as:

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z(V_{31} - V_3) = z(1-z)(V_{31} - V_{32}) \\ &= z(1-z)\big\{m(x-1)(y-1)\big(U - R_p + C_{r1}\big) - mxG_z(y-1) \\ &\quad + xym(G_z - U + S - C_{r2} + R_h) \\ &\quad + m(x-1)(y-1)(G_z - U + S - C_{r2} + R_h) \\ &\quad - myG_z(x-1) + xym\big(U - R_p + C_{r1}\big) \\ &\quad - (m-1)(x-1)(y-1)(E_d - U + S - C_{r2} + R_h) \\ &\quad - (m-1)(x-1)(y-1)\big(U - R_p + C_{r1}\big) \\ &\quad - xy(m-1)(E_d - U + S - C_{r2} + R_h) \\ &\quad - xy(m-1)\big(U - R_p + C_{r1}\big)\big\} \end{aligned}$$

Taking the first derivative of $F(z)$, then:

$$\begin{aligned} F'(z) &= \frac{dF(z)}{dz} = (1-2z)(V_{31} - V_{32}) \\ &= (1-2z)\big\{m(x-1)(y-1)\big(U - R_p + C_{r_1}\big) - mxG_z(y-1) \\ &\quad + xym(G_z - U + S - C_{r_2} + R_h) \\ &\quad + m(x-1)(y-1)(G_z - U + S - C_{r_2} + R_h) \\ &\quad - myG_z(x-1) + xym\big(U - R_p + C_{r_1}\big) \\ &\quad - (m-1)(x-1)(y-1)(E_d - U + S - C_{r_2} + R_h) \\ &\quad - (m-1)(x-1)(y-1)\big(U - R_p + C_{r_1}\big) \\ &\quad - xy(m-1)(E_d - U + S - C_{r_2} + R_h) \\ &\quad - xy(m-1)\big(U - R_p + C_{r_1}\big)\big\} \end{aligned}$$

According to the stability theorem of differential equations, the probability that the scrap recycler's strategy is in a steady state must satisfy the following formulas: $F(z) = 0$ and $F'(z) < 0$.

Proof 5. Let $J(y) = \{m(x-1)(y-1)(U - R_p + C_{r1}) - xmG_z(y-1) + mxy(G_z - U + S - C_{r2} + R_h) + m(x-1)(y-1)(G_z - U + S - C_{r2} + R_h) - my(x-1)G_z + mxy(U - R_p + C_{r1}) - (m-1)(x-1)(y-1)(E_d - U + S - C_{r2} + R_h) - (m-1)(x-1)(y-1)(U - R_p + C_{r1}) - xy(m-1)h(E_d - U + S - C_{r2} + R_h) - xy(m-1)(U - R_p + C_{r1})\}$, and then take the first-order derivative of $J(y)$ to obtain $J'(y) = (2x - 1)(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d)$, and it is easy to conclude that $J'(y) > 0$ when $x > 1/2$, so $J(y)$ is a monotonically increasing function with respect to y. When $J(y) = 0$, $y^{**} = -\ (E_d +$

$S - C_{r2} + R_h - R_p + C_{r1} - mE_d + mG_z - xE_d - xS + xC_{r2} - xR_h + xR_p - xC_{r1} + xmE_d)/\{(2x - 1)(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d)\}$. If $y < y^{**}$, it can be inferred that $J(y) < 0$, which leads to $F(z)|_{z=0} = 0$ and $F'(z)|_{z=0} < 0$, which suggests that $z = 0$ is the point of evolutionary stabilization strategy for scrap recyclers. If $y > y^{**}$, then it can be inferred that $J(y) > 0$, which leads to $F(z)|_{z=1} = 0$ and $F'(z)|_{z=1} < 0$, which indicates that $z = 1$ is an evolutionarily stable strategy point for the scrap recycler. Otherwise, i.e., $y = y^{**}$, then $J(y) = 0$ and thus $F(z) = F'(z) = 0$. Therefore, the evolutionary stabilization strategy of the scrap recycler cannot be determined.

Proof 6. $y^{**} = -(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d + mG_z - xE_d - xS + xC_{r2} - xR_h + xR_p - xC_{r1} + xmE_d)/\{(2x - 1)(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d)\}$, Taking the first-order partial derivatives of the variables of interest yields that $\frac{\partial y^{**}}{\partial m} < 0$, $\frac{\partial y^{**}}{\partial G_z} < 0$, $\frac{\partial y^{**}}{\partial R_p} < 0$, $\frac{\partial y^{**}}{\partial C_{r1}} > 0$, $\frac{\partial y^{**}}{\partial S} > 0$, $\frac{\partial y^{**}}{\partial C_{r2}} < 0$, $\frac{\partial y^{**}}{\partial R_h} > 0$, $\frac{\partial y^{**}}{\partial E_d} > 0$. Thus, y^{**} is positively correlated with C_{r1}, S, R_h, E_d, and y^{**} is negatively correlated with m, G_z, R_p, C_{r2}.

(1) Derived from Proof 5, the strategy of the scrap steel recycler varies with the changes in the strategy of the construction enterprise, with y gradually evolving from 0 to 1, and z also evolving from 0 to 1. As construction enterprises incline towards green consumption, scrap steel recyclers will also be inclined to engage in technological innovation. The strategy of the scrap steel recycler is influenced by factors such as their processing costs, carbon benefits from technological innovation, revenue from selling scrap steel, consumption subsidies for recycling scrap steel, and subsidies for technological innovation.

(2) Proof 5 demonstrates that when the inequality $\{m(x-1)(y-1)(U - R_p + C_{r1}) - xmG_z(y-1) + mxy(G_z - U + S - C_{r2} + R_h) + m(x-1)(y-1)(G_z - U + S - C_{r2} + R_h) - my(x-1)G_z + mxy(U - R_p + C_{r1}) - (m-1)(x-1)(y-1)(E_d - U + S - C_{r2} + R_h) - (m-1)(x-1)(y-1)(U - R_p + C_{r1}) - xy(m-1)(E_d - U + S - C_{r2} + R_h) - xy(m-1)(U - R_p + C_{r1})\} > 0$ holds, the evolutionary stable strategy for scrap steel recyclers is to engage in technological innovation. The threshold y^{**} is given by $y^{**} = -(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d + mG_z - xE_d - xS + xC_{r2} - xR_h + xR_p - xC_{r1} + xmE_d)/\{(2x - 1)(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d)\}$. If $y < y^{**}$, the evolutionary stable strategy for scrap steel recyclers is not to engage in technological innovation; if $y > y^{**}$, the evolutionary stable strategy is to engage in technological innovation. Otherwise, the evolutionary stable strategy for scrap steel recyclers cannot be determined.

(3) Proof 6 indicates that the technological innovation of scrap steel recyclers is related to the magnitude of government subsidies. If the government increases the consumption subsidies for scrap steel recyclers that undertake technological innovation, it will stimulate their enthusiasm. In addition, the size of the carbon benefits generated also has a positive effect on promoting technological innovation by scrap steel recyclers. It can be concluded that strengthening the economic support to scrap steel recyclers by the government can, to a certain extent, enhance the vitality of their technological innovation.

(4) The phase diagram of the strategic choices of scrap steel recyclers is determined by relevant parameters. According to the equation $y^{**} = -(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d + mG_z - xE_d - xS + xC_{r2} - xR_h + xR_p - xC_{r1} + xmE_d)/\{(2x - 1)(E_d + S - C_{r2} + R_h - R_p + C_{r1} - mE_d)\}$, we can deduce that when $y^{**} = 0$, $m_1 = -(E_d + S - C_{r2} + R_h - R_p + C_{r1} - xE_d - xS + xC_{r2} - xR_h + xR_p - xC_{r1})/(G_z - E_d + xE_d)$, and when $y^{**} = 1$, $m_2 = \{E_d + S - C_{r2} + R_h - R_p + C_{r1} - xE_d - xS + xC_{r2} - xR_h + xR_p - xC_{r1} + (2x - 1)(E_d + S - C_{r2} + R_h - R_p + C_{r1})\}/\{E_d - G_z - xE_d + (2x - 1)E_d\}$. It is reasonable to assume $0 < m_2 < m_1 < 1$. As illustrated in Figure 4 and Equation 6, D_{31} represents the probability that the scrap steel recycler will undertake technological innovation, while D_{32} represents the probability that the scrap steel recycler will not undertake technological innovation.

$$\begin{cases} D_{31} = 1 - D_{32} = 1 - \left(\int_0^1 \int_{m_2}^{m_1} y^{**} dz dm + \int_0^1 \int_0^{m_2} dz dm \right) \\ D_{32} = \int_0^1 \int_{m_2}^{m_1} y^{**} dz dm + \int_0^1 \int_0^{m_2} dz dm \end{cases} \tag{6}$$

4.4 Stability analysis of strategies for government

The government's expected revenues under the implementation of technological innovation subsidies and consumption subsidies are V_{41} and V_{42}, respectively, and the average expected revenue for both is V_4.

$$\begin{cases} V_{41} = -G - xG_p - zG_z - xyE_s \\ V_{42} = R - G - xG_p - xR - yR - zE_d \\ \qquad - xyG_d + xyG_p + 2xyR - xyE_s + xzE_d + yzE_d - 2xyzE_d \\ V_4 = mV_{41} + (1 - m)V_{42} \end{cases} \tag{7}$$

From (Equation 7), the government's replication dynamic equation can be obtained as:

$$\begin{aligned} F(m) = \frac{dm}{dt} &= m(V_{41} - V_4) = m(1 - m)(V_{41} - V_{42}) \\ &= m(1 - m)m(1 - m)(xR - R + yR + zE_d \\ &\quad - zG_Z + xyG_d - xyG_p - 2xyR - xzE_d \\ &\quad - yzE_d + 2xyzE_d) \end{aligned}$$

Taking the first derivative of $F(m)$, then:

$$\begin{aligned} F'(m) = \frac{dF(m)}{dm} &= (1 - 2m)(V_{41} - V_{42}) = (1 - 2m)m(1 - m) \\ &\left(xR - R + yR + zE_d - zG_Z + xyG_d - xyG_p \right. \\ &\left. - 2xyR - xzE_d - yzE_d + 2xyzE_d\right) \end{aligned}$$

According to the stability theorem of differential equations, the probability that the government's strategy is in a steady state must satisfy the following equations: $F(m) = 0$ and $F'(m) < 0$.

Proof 7. Let $K(z) = m(1 - m)(xR - R + yR + zE_d - zG_z + xyG_d - xyG_p - 2xyR - xzE_d - yzE_d + 2xyzE_d)$, and take the

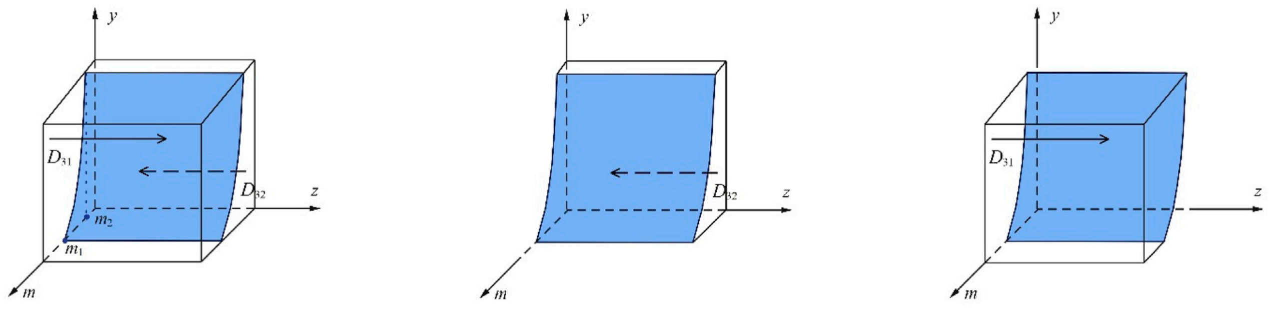

FIGURE 4
Phase diagram of strategic options for scrap recycler.

first-order partial derivatives of it to get $K'(z) = m(m-1)(G_z - E_d + xE_d + yE_d - 2xyE_d)$, obviously, $K'(z) > 0$, so $k(z)$ is a monotonically increasing function on z. $k(z) = 0, z^* = -(R - xR - yR - xyGd + xyGp + 2xyR)/(G_z - E_d + xE_d + yE_d - 2xyE_d)$. If $z < z^*$, it can be inferred that $k(z) < 0$, which leads to $F(m)|_{m=} 0 = 0$ and $F'(m)|_{m=0} < 0$, which suggests that $m = 0$ is the government's evolutionarily stable strategy point. If $z > z^*$, it can be inferred that $k(z) > 0$, which leads to $F(m)|_{m=} 1 = 0$ and $F'(m)|_{m=1} < 0$, which suggests that $m = 1$ is the government's evolutionary stabilization strategy point. Otherwise, i.e., $z = z^*$, then $k(z) = 0$ and thus $F(m) = F'(m) = 0$. Therefore, the government's evolutionary stabilization strategy cannot be determined.

Proof 8. $z^* = -(R - xR - yR - xyGd + xyGp + 2xyR)/(G_z - E_d + xE_d + yE_d - 2xyE_d)$, taking the first-order partial derivatives of its correlated variables yields, $\frac{\partial z^*}{\partial x} > 0$, $\frac{\partial z^*}{\partial R} < 0$, $\frac{\partial z^*}{\partial E_d} < 0$, $\frac{\partial z^*}{\partial G_d} > 0$, $\frac{\partial z^*}{\partial G_p} < 0$, $\frac{\partial z^*}{\partial G_z} > 0$, so z^* is positively correlated with x, G_d, G_z, and z^* is negatively correlated with R, E_d, G_p.

(1) According to Proof 7, the government's strategy varies with the changes in the strategies of scrap steel recyclers, where z gradually evolves from 0 to 1, and m also evolves from 0 to 1. As scrap steel recyclers tend to engage in technological innovation, the government will be inclined to adopt subsidies for technological innovation and research and development. The government's strategy is influenced by its consumption subsidies and technological innovation subsidies to steel manufacturers, construction companies, and scrap steel recyclers. The magnitude of various subsidy amounts will affect the government's strategic choices to varying degrees.

(2) Proof 7 shows that the government's evolutionary stabilization strategy is to implement a technological innovation subsidy when $m(1-m)(xR - R + yR + zE_d - zG_z + xyG_d - xyG_p - 2xyR - xzE_d - yzE_d + 2xyzE_d) > 0$, with a threshold $z^* = -(R - xR - yR - xyGd + xyGp + 2xyR)/(G_z - E_d + xE_d + yE_d - 2xyE_d)$, if $z < z^*$, the government's evolutionary stabilization strategy is to implement a consumption subsidy; if $z > z^*$, the government's evolutionary stabilization strategy is to implement a technological innovation subsidy. Otherwise, the government's evolutionary stabilization strategy cannot be determined.

(3) According to Proof 8, whether the government increases the consumption subsidies for green consumption by construction enterprises or the technological innovation subsidies for scrap steel recyclers, it can enhance the enthusiasm of scrap steel recyclers for technological innovation. However, the increase in credibility due to government consumption subsidies, as well as the technological innovation subsidies to steel manufacturers and the consumption subsidies to scrap steel recyclers, have a dampening effect on the technological innovation by scrap steel recyclers. Therefore, for the government, it is crucial to strike a balance between consumption subsidies and technological innovation subsidies. Over a certain period, the

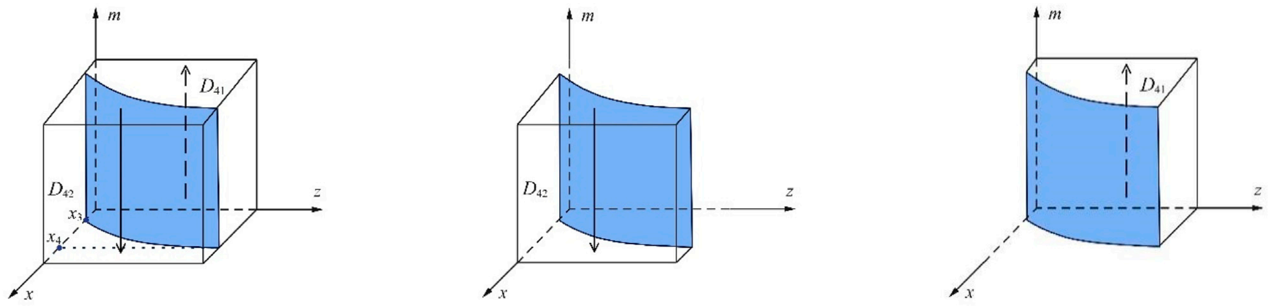

FIGURE 5
Phase diagram of strategic options for government.

TABLE 3 Evolutionarily stable analysis of equilibrium points of replication dynamic system under consumption subsidies.

Equilibrium point	$\lambda_1; \lambda_2; \lambda_3; \lambda_4$	Sign	Stability
(0,0,0,0)	$P_q - U; -R; E_d + S - C_{r2} + R_h - R_p + C_{r1}; R_P - P_q + S_c - C_1 + C_0 + S_r + T$	$(+, -, \times, \times)$	Unstable
(1,0,0,0)	$0; 0; w_d + U + G_d - P_q; P_q - R_p - S_c + C_1 - C_0 - S_r - T$	$(0, 0, \times, +)$	Unstable
(0,1,0,0)	$0; 0; U - P_q; E_s + P_t - R_p + S_c - C_1 + C_0 + S_r + T$	$(0, 0, -, +)$	Unstable
(0,0,1,0)	$P_q - U; E_d - R - G_z; C_{r2} - S - E_d - R_h + R_p - C_{r1}; R_h - P_q + S_c - C_1 + C_0 + S_r + T$	$(+, \times, \times, \times)$	Unstable
(1,1,0,0)	$G_d - G_p - R; P_t - U - G_d - w_d; E_d + S - C_{r2} + R_h - R_P + C_{r1}; R_p - P_t - E_s - S_c + C_1 - C_0 - S_r - T$	$(\times, \times, \times, -)$	ESS(a)
(1,0,1,0)	$0; -G_z; w_d + U + G_d - P_t; P_q - R_h - S_c + C_1 - C_0 - S_r - T$	$(0, -, \times, +)$	Unstable
(0,1,1,0)	$0; U - P_q; -G_z; E_s + P_t - R_h + S_c - C_1 + C_0 + S_r + T$	$(0, -, -, +)$	Unstable
(1,1,1,0)	$P_t - U - G_d - w_d; G_d + E_d - G_p - R - G_z; C_{r2} - S - E_d - R_h + R_p - C_{r1}; R_h - P_t - E_s - S_c + C_1 - C_0 - S_r - T$	$(\times, \times, \times, -)$	ESS(b)

Note: × represents an indeterminate symbol, ESS stands for Evolutionarily Stable Strategy, (a) indicates that the conditions $G_d < G_p + R$, $P_t < U + G_d + w_d$, $C_{r2} + R_p > E_s + S + R_h + C_{r1}$ are satisfied, (b) indicates that the conditions $P_t < U + G_d + w_d$, $G_d + E_d < G_p + R + G_z$, $C_{r2} + R_p < S + E_d + R_h + C_{r1}$ are satisfied.

government needs to establish reasonable subsidy levels based on feedback from various stakeholders and market research.

$$\begin{cases} D_{41} = 1 - D_{42} = 1 - \left(\int_0^1 \int_{x_3}^{x_4} z^* dxdm + \int_0^1 \int_{x_4}^{1} dxdm \right) \\ D_{42} = \int_0^1 \int_{x_3}^{x_4} z^* dxdm + \int_0^1 \int_{x_4}^{1} dxdm \end{cases} \tag{8}$$

(4) The phase diagram chosen by the government strategy is determined by the relevant parameters, according to $z^* = -(R - xR - yR - xyGd + xyGp + 2xyR)/(G_z - E_d + xE_d + yE_d - 2xyE_d)$, which means that when $z^* = 0$, $x_3 = (R - yR)/(R + yG_d - yG_p - 2yR)$, when $z^* = 1$, $x_4 = -(R - E_d + G_z + yE_d - yR)/(E_d - R - yG_d - 2yE_d + yG_p + 2yR)$, it may as well be set $0 < x_3 < x_4 < 1$. As shown in Figure 5 and Equation 8, D_{41} denotes the probability of the government's implementation of technological innovation subsidies, and D_{42} denotes the probability of the government's implementation of consumption subsidies.

4.5 Stability analysis of the four-party strategy combination

The previous section mainly analyzes the evolutionary stability of each of the four parties, and the following section analyzes the evolutionary stability strategy and equilibrium point state under the joint action of the four parties.

$$\begin{cases} F(x) = dx/dt = x(V_{11} - V_1) = x(1-x)(V_{11} - V_{12}) \\ F(y) = dy/dt = y(V_{21} - V_2) = y(1-y)(V_{21} - V_{22}) \\ F(z) = dz/dt = z(V_{31} - V_3) = z(1-z)(V_{31} - V_{32}) \\ F(m) = dm/dt = m(V_{41} - V_4) = m(1-m)(V_{41} - V_{42}) \end{cases}$$

Based on the replicator dynamics equations of the four-player game system, the corresponding Jacobian matrix can be derived. The stability of strategies in the four-player game can be judged by the first Lyapunov method: if all the eigenvalues of the Jacobian matrix are negative, then the equilibrium point is an Evolutionarily Stable Strategy (ESS). If at least one of the

TABLE 4 Evolutionarily stable analysis of equilibrium points of replication dynamic system under technological innovation subsidies.

Equilibrium point	$\lambda_1; \lambda_2; \lambda_3; \lambda_4$	Sign	Stability
(0,0,0,1)	$R; P_q - U; G_z + S - C_{r_2} + R_h - R_h + C_{r_1}; G_p - P_q + R_p + S_c - C_1 + C_0 + S_r + T$	$(+, +, \times, \times)$	Unstable
(1,0,0,1)	$0; G_z; w_d + U - P_q; P_q - G_p - R_p - S_c + C_1 - C_0 - S_r - T$	$(0, +, \times, \times)$	Unstable
(0,1,0,1)	$0; G_z; U - P_q; G_p + P_q - R_p + S_c - C_1 + C_0 + S_r + T$	$(0, +, -, \times)$	Unstable
(0,0,1,1)	$P_q - U; R - E_d + G_z; C_{r2} - S - G_z - R_h + R_p - C_{r1}; G_p - P_q + R_h + S_c - C_1 + C_0 + S_r + T$	$(+, +, \times, \times)$	Unstable
(1,1,0,1)	$G_p - G_d + R; P_q - U - w_d; G_z + S - C_{r2} + R_h - R_p + C_{r1}; R_p - P_q - G_p - S_c + C_1 - C_0 - S_r - T$	$(\times, \times, \times, -)$	ESS(c)
(1,0,1,1)	$G_z; -G_z; w_d + U - P_q; P_q - G_p - R_h - S_c + C_1 - C_0 - S_r - T$	$(+, -, \times, \times)$	Unstable
(0,1,1,1)	$G_z; U - P_q; -G_z; G_p + P_q - R_h + S_c - C_1 + C_0 + S_r + T$	$(+, -, -, \times)$	Unstable
(1,1,1,1)	$P_q - U - w_d; G_p - E_d - G_d + R + G_z; C_{r2} - S - G_z - R_h + R_p - C_{r1}; R_h - P_q - G_p - S_c + C_1 - C_0 - S_r - T$	$(\times, \times, \times, -)$	ESS(d)

Note: × represents an indeterminate symbol, ESS stands for Evolutionarily Stable Strategy, (a) indicates that the conditions $G_p + R < G_d$, $P_q < U + w_d$, $G_z + S + R_h + C_{r1} < C_{r2} + R_p$ are satisfied, (b) indicates that the conditions $P_q < U + w_d$, $R + G_z + G_p < E_d + G_d$, $C_{r2} + R_p < S + G_z + R_h + C_{r1}$ are satisfied.

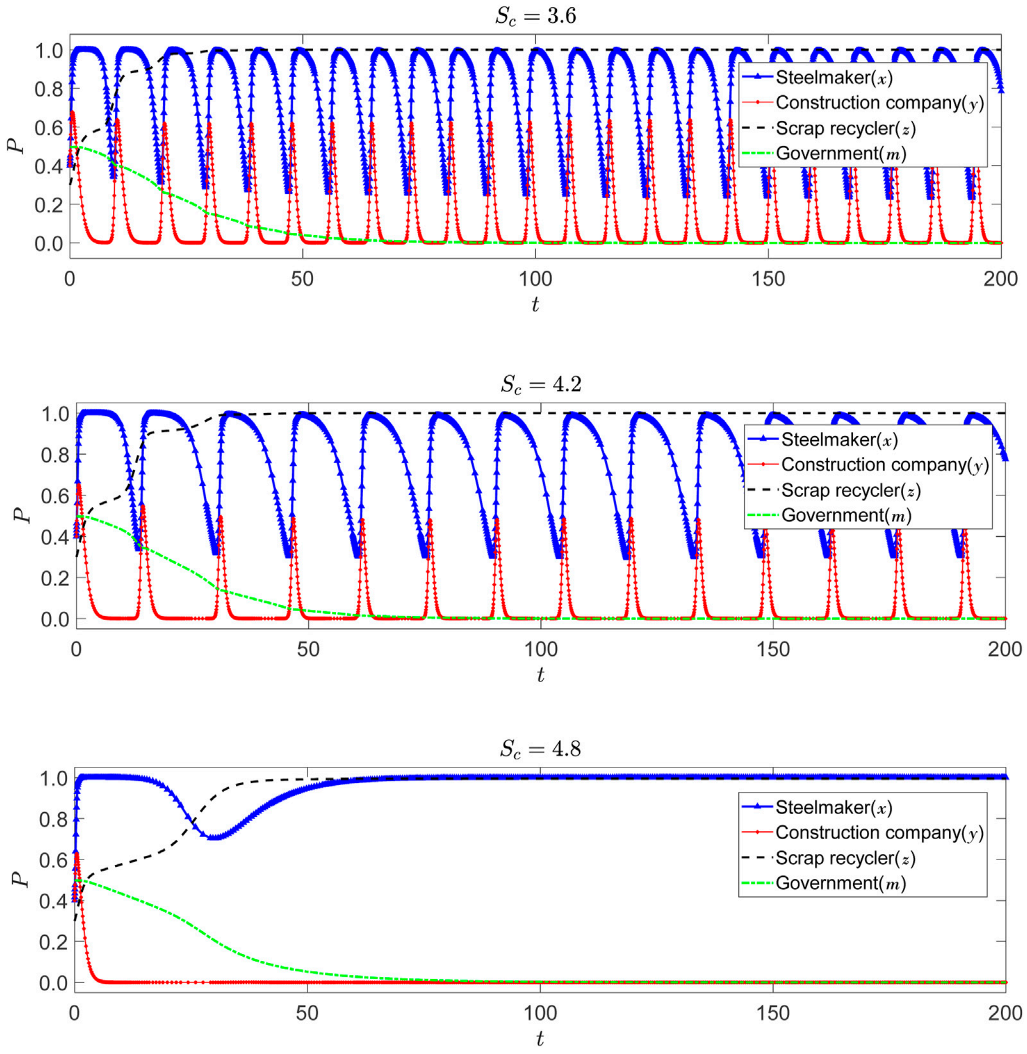

FIGURE 6
Impact of S_c on the evolution of the system.

eigenvalues of the Jacobian matrix is positive, then the equilibrium point is unstable. If all the eigenvalues of the Jacobian matrix are negative except for one that equals zero, then the equilibrium point is at a critical state, and its stability is uncertain. Moreover, the stable solution in a multi-population evolutionary game must be a strict Nash equilibrium, that is, a pure strategy equilibrium. Therefore, in the four-player evolutionary game, this paper attempts to analyze the stability of 16 pure strategy equilibrium points.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} & \frac{\partial F(x)}{\partial m} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} & \frac{\partial F(y)}{\partial m} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} & \frac{\partial F(z)}{\partial m} \\ \frac{\partial F(m)}{\partial x} & \frac{\partial F(m)}{\partial y} & \frac{\partial F(m)}{\partial z} & \frac{\partial F(m)}{\partial m} \end{bmatrix}$$

4.5.1 Stability analysis of strategy combination under consumption subsidy

The asymptotic stability analysis of the equilibrium point of this replicated dynamic system is shown in Table 3 when the government's stabilization strategy is to implement consumption subsidies, i.e., when the condition $m(1-m)(xR - R + yR + zE_d - zG_z + xyG_d - xyG_p - 2xyR - xzE_d - yzE_d + 2xyzE_d) < 0$ is satisfied.

Table 3 indicates the existence of two possible stable strategies, namely, (1,1,0,0) and (1,1,1,0). The strategy (1,1,0,0) signifies that the steel manufacturer engages in technological innovation, the construction company adopts green consumption practices, the scrap steel recycler does not engage in technological innovation, and the government implements consumption subsidies. At this point, the conditions $G_d < G_p + G_r$, $P_t < D_s + G_d + D_c$, and $R_c + R_p > G_n + R_b + R_h + R_t$ are met. This implies that the government's credibility is greater than the difference between the consumption subsidies for construction companies and the technological innovation subsidies for steel manufacturers. The sum of the

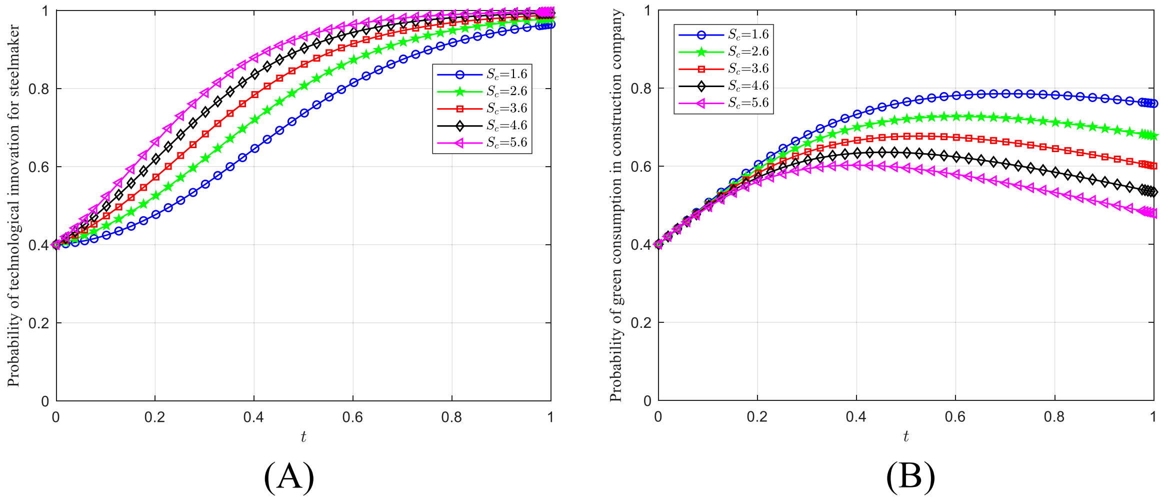

FIGURE 7
(A, B) Impact of S_c on steelmaker and construction company.

carbon benefits from green consumption by construction companies, the income from providing scrap steel, and the consumption subsidies is greater than the price of green products. The difference in processing costs before and after technological innovation by the scrap steel recycler is greater than the sum of the income difference from providing scrap steel, the technological innovation carbon benefits, and the consumption subsidies. When $G_d + G_n < G_p + G_r + G_z$ and $R_c + R_p < R_b + G_n + R_h + R_t$, the replicator dynamics system will stabilize at (1,1,1,0). With the scrap steel recycler participating in technological innovation, the government will implement certain technological innovation subsidies and consumption subsidies for the scrap steel recycler. At this time, the government's credibility is greater than the difference between the consumption subsidies and technological innovation subsidies for all parties. Contrary to some conclusions of (1,1,0,0), the difference in processing costs before and after technological innovation by the scrap steel recycler will be less than the sum of the income difference from providing scrap steel, the technological innovation carbon benefits, and the consumption subsidies.

The preceding analysis illustrates the necessity for the government to exert a guiding influence on the procurement of green products, while steel manufacturers must also manage product pricing judiciously. For scrap steel recyclers to be incentivized to undertake technological innovation, it is imperative that their overall revenue surpasses the differential in costs associated with innovation before and after its implementation, thereby integrating them into the transformation towards low-carbon steel production. Given the current landscape of the steel industry, technological innovation stands as a pivotal element for carbon emission reduction. However, there is a dearth of impetus for carbon reduction technological innovation at present. To facilitate the adoption of technologically innovative production paradigms by steel manufacturers, it is essential for the government to enact technological innovation subsidies as a priority. This strategic approach will foster an environment where engaging in technological innovation becomes a stable strategy for both the steel manufacturers and the scrap steel recyclers.

4.5.2 Stability analysis of strategy combination under technological innovation subsidies

When the government's stable strategy is to provide subsidies for investment in technological innovation, specifically when the condition $m(1-m)(xR - R + yR + zE_d - zG_z + xyG_d - xyG_p - 2xyR - xzE_d - yzE_d + 2xyzE_d) < 0$ is satisfied, the asymptotic stability analysis of the equilibrium point within the replicator dynamics system is depicted in Table 4.

Table 4 demonstrates that when the government implements technological innovation subsidies, there are two possible stable strategies: the points (1,1,0,1) and (1,1,1,1). The strategy (1,1,0,1) indicates that the steel manufacturer engages in technological innovation, the construction company practices green consumption, the scrap steel recycler does not engage in technological innovation, and the government provides subsidies for technological innovation. At this juncture, the conditions $G_p + G_r < G_d$, $P_q < D_s + D_c$, and $G_z + R_b + R_h + R_t < R_c + R_p$ are met. This means that the government's credibility exceeds the difference between the technological innovation subsidies for steel manufacturers and the consumption subsidies for construction companies. The sum of the carbon benefits from green consumption by construction companies and the income from providing scrap steel is greater than the price of conventional products. The difference in processing costs before and after technological innovation by the scrap steel recycler is greater than the sum of the income difference from providing scrap steel, the technological innovation carbon benefits, and the technological innovation subsidies.

As the net income of the scrap steel recycler increases, that is, when $R_c + R_p < R_b + G_z + R_h + R_t$, the scrap steel recycler undertakes technological innovation. At this point, the net income from the government's implementation of technological innovation subsidies also gradually increases, satisfying

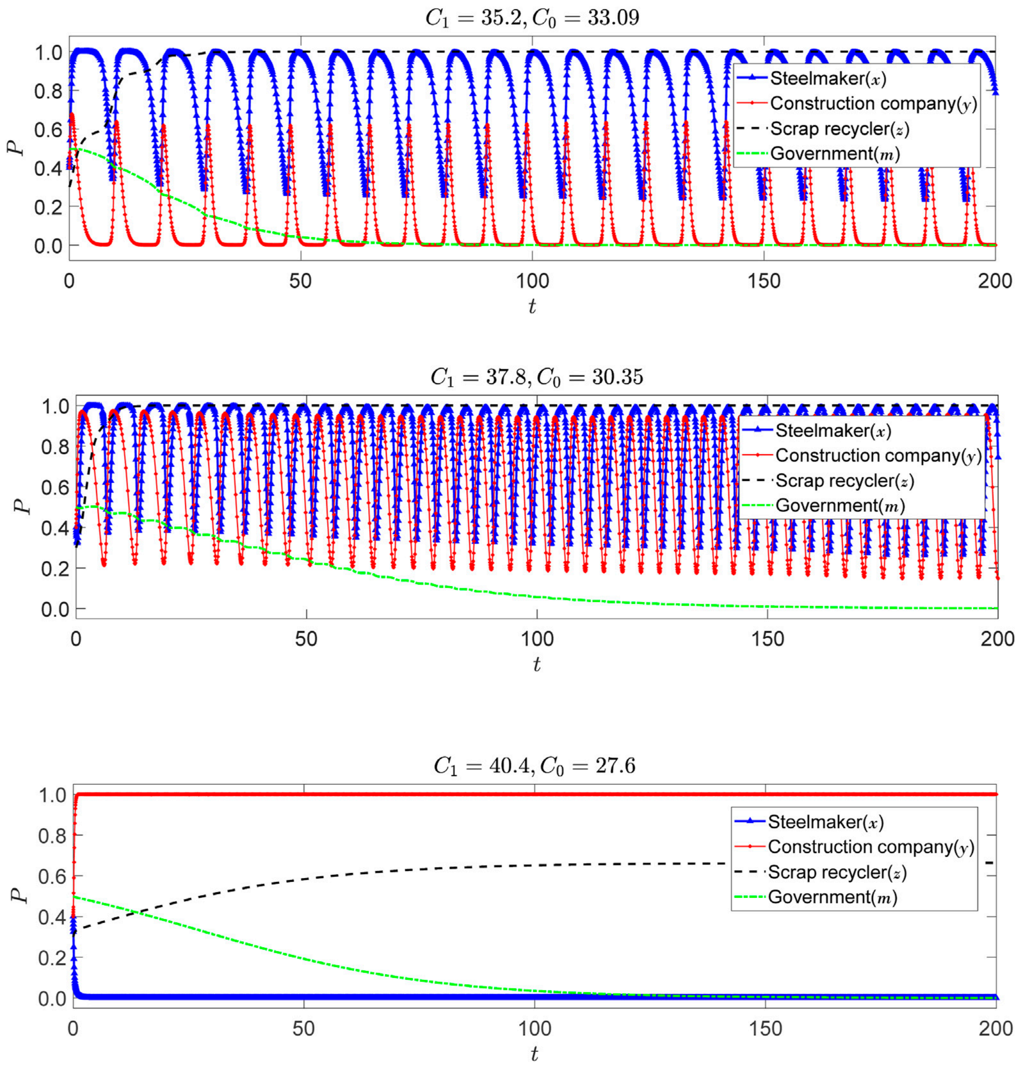

FIGURE 8
Effect of C_1, C_0 on system evolution.

$G_r + G_z + G_p < G_n + G_d$, and the system stabilizes at (1,1,1,1). This is also the most ideal state within the game system, where both the steel manufacturer and the scrap steel recycler engage in technological innovation, the construction company opts for green consumption, and the government provides subsidies for technological innovation. During the processes of steel production, consumption, and recycling, the government's various subsidies need to be formulated based on the cost of product production and pricing. The interests of all parties are interwoven, and further analysis and discussion will be conducted in the subsequent simulation analysis section.

5 Numerical simulation and discussion

The analysis results presented earlier indicate that the strategies of the steel manufacturer, construction company, scrap steel recycler, and government are interdependent. To more intuitively demonstrate the impact of key elements in the replicator dynamics system on the evolutionary process and outcomes of the multi-party game, numerical simulations of the evolutionary trajectories of each game participant were conducted using MATLAB 2021b software.

The construction industry holds a major share of the demand in the steel market. Therefore, this paper selects the construction company as the downstream consumer of the steel manufacturer. Considering that the steel manufacturer offers a wide range of steel products with significant price differences, we chose the procurement and recycling prices of rebar steel as the data source for the numerical simulation. Through investigation, it was found that the monthly average price of rebar steel HS400E (20 mm) from 20 steel manufacturers in Jiangxi Province is 34.66 (yuan/100 tons). It was also learned that the average untaxed cost of rebar steel from 31 inland steel mills in mainland China is 33.49 (yuan/100 tons). In combination with the price of recycled steel rebar (thickness greater than 6 mm) from a certain environmental protection industry company in Jiangxi, which is 26.60 (yuan/100 tons) (Data sources:https://www.mysteel.com), the specific parameters for this paper are set as follows: $S_r = 0.10$,

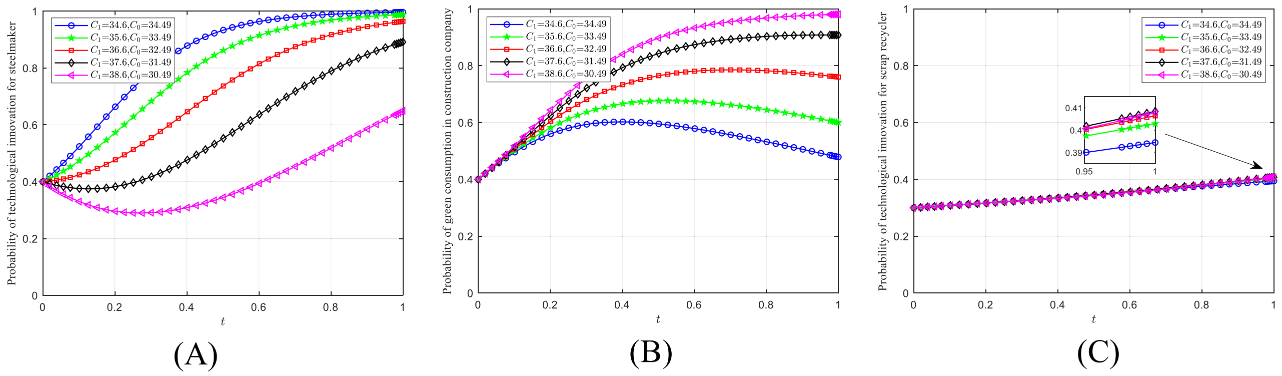

FIGURE 9
(A–C) Impact of $\boldsymbol{C_1}$, $\boldsymbol{C_0}$ on steelmaker, construction company and scrap recycler.

$C_1 = 35.60$, $C_0 = 33.49$, $T = 1.20$, $S_c = 3.60$, $P_t = 37.34$, $P_q = 34.66$, $w_d = 8.15$, $U = 26.60$, $R_h = 30.80$, $R_P = 29.30$, $C_{r2} = 2.60$, $C_{r1} = 1.50$, $S = 0.30$, $R = 0.15$, $G_p = 0.06$, $G_d = 0.24$, $E_d = 0.04$, $G_z = 0.06$, $E_s = 0.05$, $G = 0.08$. The initial strategic choices of the game participants are set as $x = 0.4$, $y = 0.4$, $z = 0.3$, $x = 0.5$.

5.1 Impact of carbon benefits on system evolution for steelmaker

Figure 6 demonstrates that the carbon benefits derived from technological innovation in the steel manufacturing sector are a key determinant of the strategic evolutionary trends for both steel manufacturers and construction enterprises. Let the set S_c be defined as $\{1.6, 2.6, 3.6, 4.6, 5.6\}$. It is apparent from Figure 7A, B that with the increase in carbon benefits from technological innovation S_c, steel manufacturers are progressively inclined towards embracing technological innovation in their production processes. However, such innovation in steel manufacturing is likely to result in higher production costs, which will subsequently drive up the prices of steel products. Consequently, construction enterprises, prioritizing their own revenue, may lean towards purchasing conventional products. Therefore, it is imperative that while the government provides technological innovation subsidies to steel manufacturers, it should also extend consumption subsidies to construction companies downstream. This dual approach will incentivize the purchase of green products by construction companies, thereby stimulating steel manufacturers to pursue technological innovation through market demand. Such a strategy will not only encourage the low-carbon transition of steel manufacturers but also contribute to the achievement of carbon reduction goals.

5.2 Impact of production costs of steelmaker on the evolution of the system

Figure 8 indicates that the production cost of steel manufacturers plays a crucial role in the evolution of strategies within the four-party game. Let $C_1 = \{34.6, 35.6, 36.6, 37.6, 38.6\}$ and $C_0 = \{34.49, 33.49, 32.49, 31.49, 30.49\}$. It is evident from Figure 9A, B that altering the difference $(C_1 - C_0)$ significantly impacts both steel manufacturers and construction companies. As the disparity $(C_1 - C_0)$ widens, steel manufacturers tend towards traditional production models, while construction companies lean towards green consumption. When the cost difference before and after technological innovation by steel manufacturers is small, they are inclined towards innovation due to the influence of carbon benefits and other potential gains from technological innovation. However, as this cost difference increases, this inclination diminishes gradually, yet it still approaches 1, suggesting that technological innovation by steel manufacturers is an inevitable trend. For the government, reasonably adjusting the subsidy mechanism is particularly important for carbon emission reduction in the steel industry. For construction companies, the greater the cost difference $(C_1 - C_0)$, the more they are inclined towards green consumption. Due to the impact of the cost difference $(C_1 - C_0)$, the price of steel products from steel manufacturers will inevitably rise, and as prices increase, the carbon benefits from purchasing green products by construction companies also increase, ultimately influencing the strategic choices of construction companies. Additionally, Figure 9C shows that the cost difference $(C_1 - C_0)$ also has a subtle effect on scrap steel recyclers. Although this impact is not significant, it generally increases the probability of technological innovation by scrap steel recyclers, indicating that technological innovation by steel manufacturers has a potential influence on the strategic evolution of scrap steel recyclers.

5.3 Impact of government credibility on system evolution

Figure 10 illustrates that the government's credibility significantly influences the evolutionary process and outcomes of the strategies within the four-party game, with the most substantial impact on the strategic evolution trend of the government itself. Consequently, we define R as $\{0.12, 1.12, 2.12, 3.12, 4.12\}$ to examine the influence of the government's credibility on the strategic evolution trends of both the government and the downstream construction companies. Observations from Figure 11A indicate

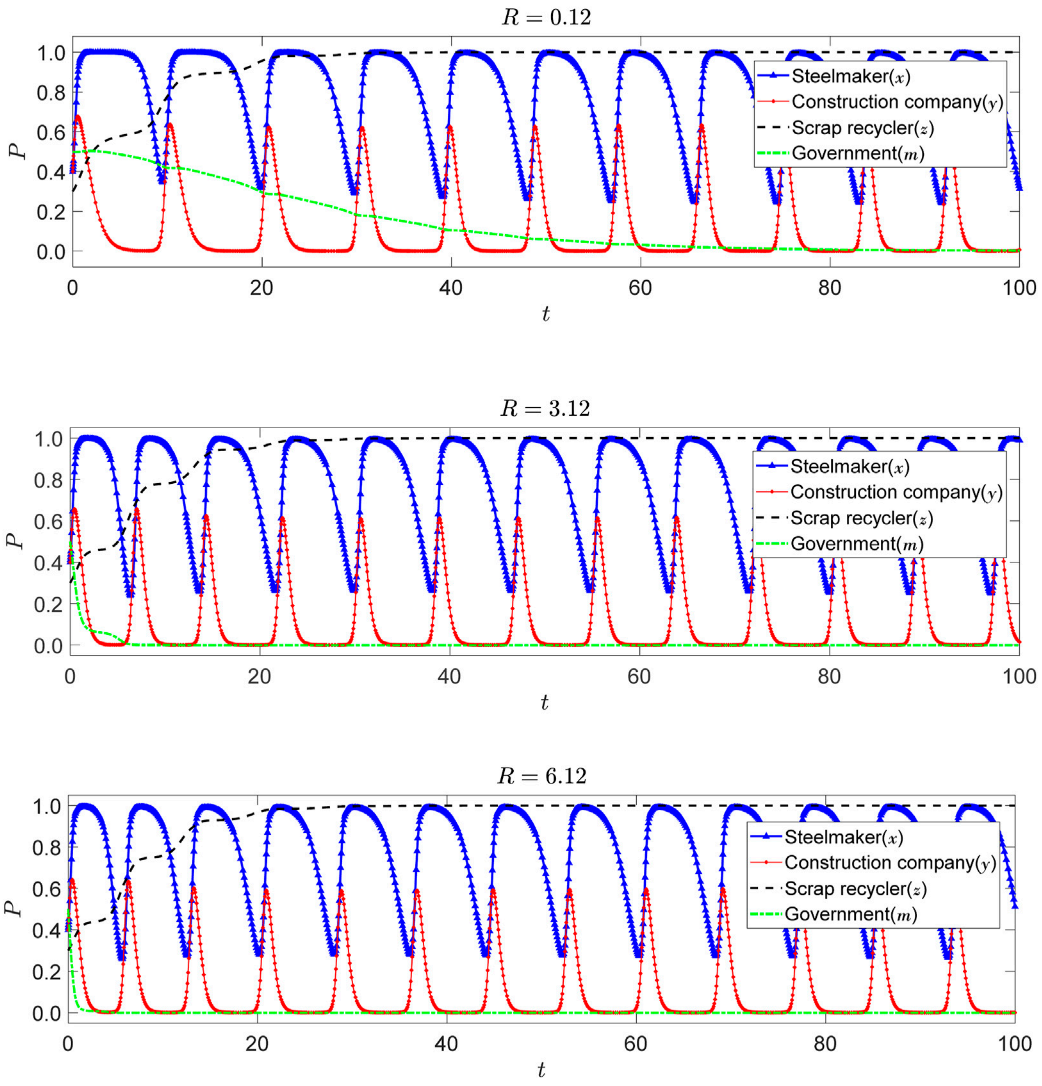

FIGURE 10
Effect of ***R*** on systematic evolution.

that an increase in R prompts the government to favor the implementation of consumption subsidies, substantiating the notion that enhanced credibility will likely result in higher costs for the government's consumption subsidy programs. It is imperative for the government to balance its net revenue against budgetary constraints to effectively manage the optimal level of subsidies.

Furthermore, Figure 11B discloses that the probability of green consumption by construction companies initially rises with an increase in R, followed by a subsequent decline. This suggests that while the government's consumption subsidies can provide an initial impetus for green consumption among construction companies, the effectiveness of this incentive diminishes over time. Even with rising government credibility, the motivation for green consumption behavior among downstream construction companies does not remain consistently high. In light of these findings, the government may need to explore alternative subsidy policies to encourage green consumption, potentially leveraging market demand to stimulate technological innovation within the steel manufacturing sector.

5.4 Impact of scrap recyclers' processing costs on system evolution

Figure 12 indicates that the processing costs of scrap steel recyclers exert a notable influence on the strategic evolution of the recyclers themselves, as well as that of steel manufacturers and construction companies. By examining the impact of the differential $(C_{r2} - C_{r1})$ on the evolutionary trajectories of these three stakeholders, and setting C_{r1} to $\{1.3, 1.4, 1.5, 1.6, 1.7\}$ and C_{r2} to $\{2.4, 2.5, 2.6, 2.7, 2.8\}$, the findings from Figure13A demonstrate that an increasing disparity in $(C_{r2} - C_{r1})$ leads to a marked reduction in the likelihood of technological innovation by scrap steel recyclers. This underscores the significance of processing costs as a determinant in the decision-making process regarding technological innovation by recyclers. With enhanced technological innovation subsidies and consumer subsidies from the government, the propensity for such innovation by scrap steel recyclers is likely to increase, as they weigh the costs of innovation against the subsidies they receive. Figure 13B elucidates that steel

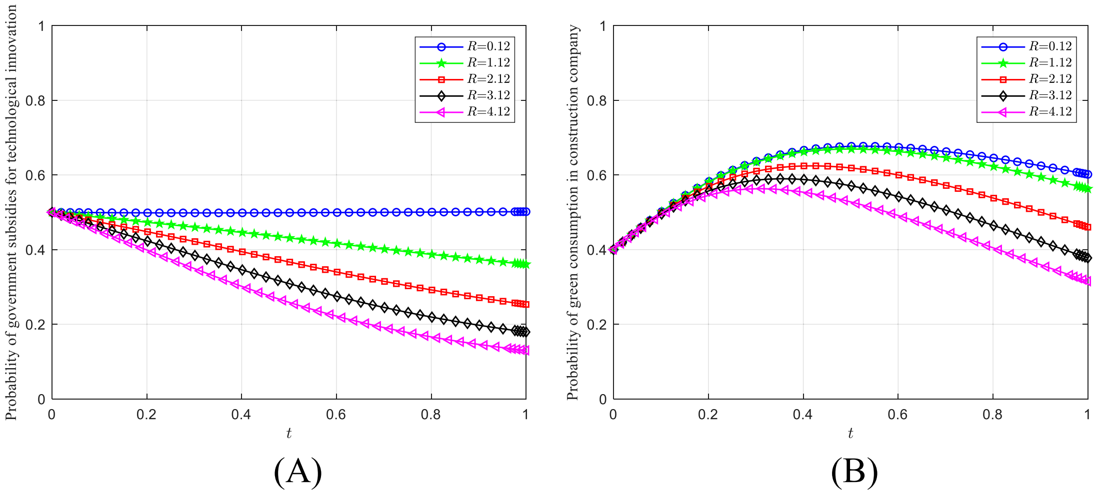

FIGURE 11
(A, B) Impact of ***R*** on government and construction company.

manufacturers are increasingly inclined towards technological innovation as the differential in processing costs before and after such innovation by scrap steel recyclers grows. This inclination stems from the fact that an increase in processing costs post-innovation among recyclers results in higher prices for the raw materials supplied to steel manufacturers, necessitating the adoption of innovation to bolster profitability.

Furthermore, Figure 13C reveals that the probability of green consumption by construction companies exhibits a downward trend in response to the differential $(C_{r2} - C_{r1})$. This trend can be attributed to the influence exerted by the strategies of scrap steel recyclers on steel manufacturers, which subsequently affects the strategic preferences of construction companies.

5.5 Impact of government subsidies for technological innovation on system evolution

Figure 14 demonstrates that the government's technological innovation subsidies exert a notable influence on the evolutionary dynamics of all four participants within the game system. In the context of sensitivity analysis, the parameters are adjusted as follows: G_p is set to $\{0.06, 0.16, 0.26, 0.36, 0.46\}$ and G_z to $\{0.05, 0.15, 0.25, 0.35, 0.45\}$. Observations from Figure 15A–C reveal that an increase in the government's technological innovation subsidies prompts steel manufacturers to lean towards technologically innovative production models, underscoring the positive motivational role of government subsidies on the technological innovation of steel manufacturers. The probability of green consumption by construction companies exhibits an initial rise followed by a subsequent decline. This trend can be attributed to the fact that technological innovation by steel manufacturers augments the supply of green products in the market, which initially boosts the likelihood of green consumption by construction companies. When this probability begins to decline, it suggests that the government should intervene with consumption subsidies to incentivize the purchase of green products by construction companies.

Furthermore, the probability of technological innovation by scrap steel recyclers also experiences a minor increase due to the marked enhancement in government subsidies. This indicates that there is a reciprocal influence among steel manufacturers, construction companies, and scrap steel recyclers, where the strategic choices of one can significantly sway the strategic propensities of the others. Considering the considerable costs associated with technological innovation subsidies, the government, prioritizing its own interests, is likely to transition from focusing on technological innovation subsidies to consumption subsidies over time. Figure 15D substantiates the finding that the likelihood of the government providing technological innovation subsidies diminishes with an increase in the subsidy amount.

5.6 Impact of government consumption subsidies on system evolution

From Figure 16, it is evident that government consumption subsidies have a significant impact on the evolutionary trends of steel manufacturers, construction enterprises, and the government itself. To further investigate the influence of subsidy amounts, we have established the following sets: $G_d = \{0.24, 0.48, 0.96, 1.92, 3.84\}$, $E_s = \{0.05, 0.1, 0.2, 0.4, 0.8\}$, and $E_d = \{0.04, 0.08, 0.16, 0.32, 0.64\}$. Figure 17A illustrates that as the amount of government consumption subsidies increases, steel manufacturers are more inclined to adopt technological innovations in their production models, and the likelihood of green consumption by construction enterprises also rises. This suggests that government subsidies, when provided at a certain level, can effectively encourage green production and consumption practices in both the steel manufacturing and construction industries. The fact that steel manufacturers acquire scrap steel from recyclers, thereby securing both raw materials for steelmaking and receiving subsidy income from the government, serves as a

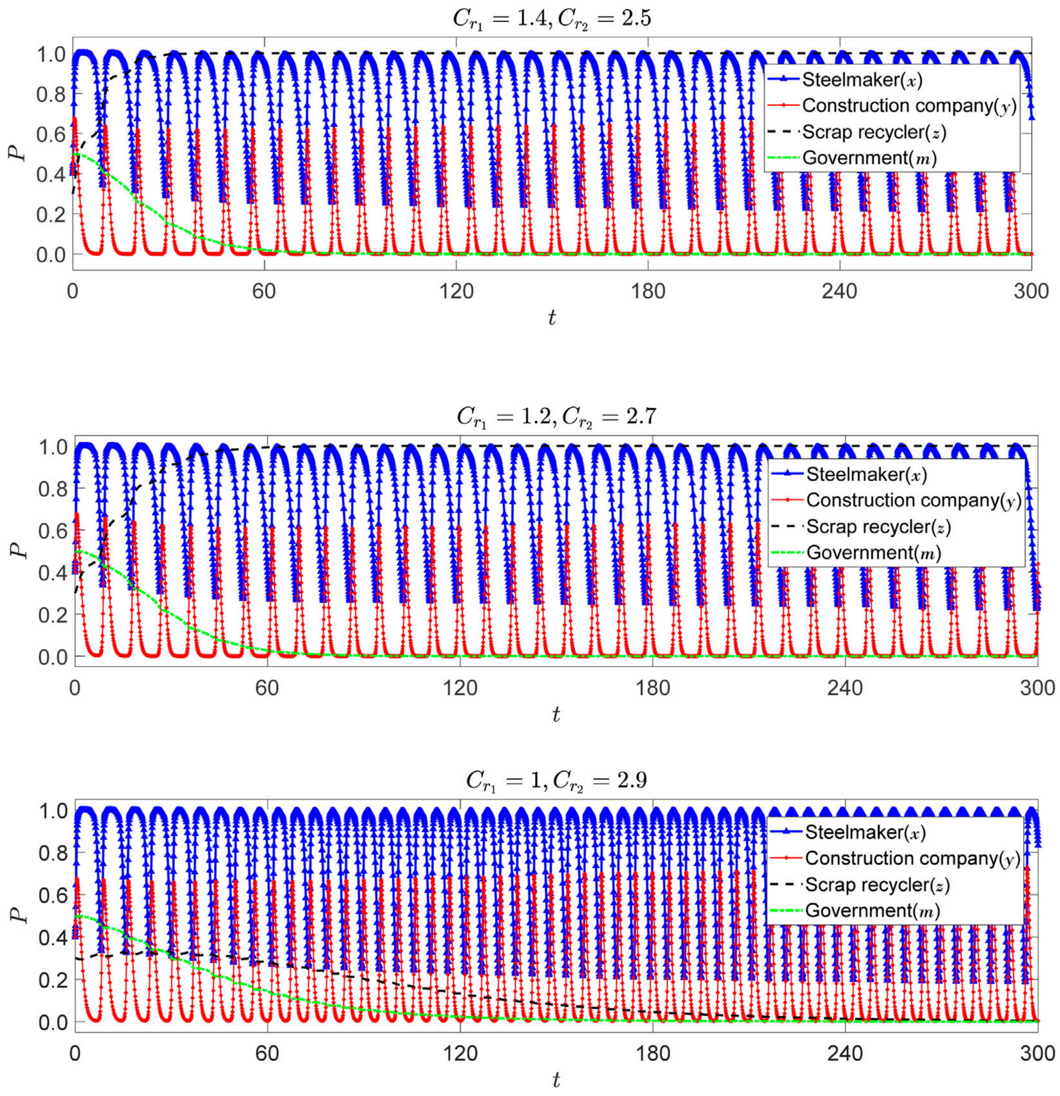

FIGURE 12
Effect of C_{r1} and C_{r2} on system evolution.

strong incentive for them to innovate technologically and engage in green production. Figure 17B indicates that consumption subsidies, acting as a direct source of revenue for green consumption by construction enterprises, significantly enhance the probability of purchasing green products. The larger the subsidy amount, the greater the propensity of construction enterprises towards green consumption. Furthermore, as consumption subsidies grow, the government may place greater emphasis on technological innovation subsidies. Figure 17C confirms that the probability of government technological innovation subsidies increases with the rise in consumption subsidies. As the sole incentive of consumption subsidies diminishes over time, appropriate technological innovation subsidies may be utilized as an additional incentive by the government. Lastly, the impact of government consumption subsidies on scrap steel recyclers is also revealed. Figure 17D demonstrates that government consumption subsidies do indeed provide a certain level of incentive for scrap steel recyclers, further integrating them into the green production cycle.

5.7 Impact of government subsidy mechanisms

To further validate the feasibility and effectiveness of government subsidy mechanisms in promoting various stakeholders' actions, we consider two states: $m = 0$ representing the implementation of consumption subsidies, and $m = 0.9$ representing the implementation of technological innovation subsidies. We conduct a simulation analysis of the evolutionary process of different initial strategies among steel manufacturers, construction enterprises, and scrap steel recyclers in a three-dimensional space. Figure 18 reveals that when $m = 0$, that is, when the government implements consumption subsidies, the strategy choices of steel manufacturers, construction enterprises, and scrap steel recyclers fluctuate due to various factors such as the size of subsidies provided by the government, production costs, and carbon earnings. This fluctuation prevents the formation of a stable strategy. When $m = 0.9$, indicating that the government can

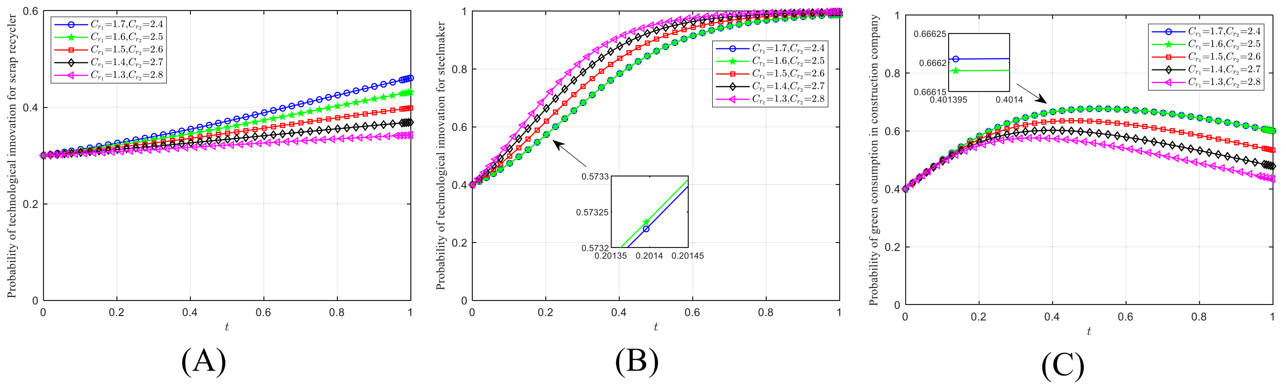

FIGURE 13
(A–C) Impact of C_{r1}, C_{r2} on scrap recycler, steelmaker and construction company.

maintain a certain level of probability for technological innovation subsidies, although a stable strategy is not formed, the probability of steel manufacturers and scrap steel recyclers engaging in technological innovation significantly increases, gradually approaching unity. Meanwhile, the strategy choices of construction enterprises do not exhibit significant changes, remaining at a certain level of probability for non-green consumption strategies. This is consistent with the results of the stability analysis of strategy combinations under different government subsidy policies mentioned earlier.

6 Discussion

This paper presents findings obtained by constructing and solving an evolutionary game model involving four parties. The discussion is divided into two parts: first, an introduction to the research results, followed by policy implications for stakeholders in steel production, consumption, and recycling. The aim is to foster technological innovation across the entire steel industry and facilitate a low-carbon transition, thereby contributing to the nation’s Dual-carbon goals.

6.1 Research findings

In this paper, we have constructed and theoretically analyzed a four-way evolutionary game model, demonstrating that it supports four Evolutionary Stable Strategies (ESS). The system’s optimal evolutionary stability point is identified as (1,1,1,1), with the necessary conditions for this stability being $P_q < U + w_d$, $R + G_z + G_p < E_d + G_d$, and $C_{r2} + R_p < S + G_z + R_{\hbar} + C_{r1}$. Through numerical simulations, we have assessed the impact of six key factors on these four strategic approaches, yielding significant findings. Additionally, we have analyzed the influence of government subsidy mechanisms on the gaming system, focusing on the stable strategy tendencies of steel manufacturers, construction companies, and scrap recyclers in response to technological innovation subsidies and consumption subsidies. The principal research findings are summarized below:

(1) The paramount factor influencing carbon emission reduction across the steel production, sales, and recycling stages is the production cost of steel manufacturers. This cost differential $(C_1 - C_0)$ post technological innovation significantly impacts the strategic decisions of construction enterprises, scrap recyclers, and the government. While previous studies have focused on the additional production costs incurred during technological innovation, they have overlooked the broader implications of the cost differential (Chen and Wang, 2023). We find that a modest production cost differential correlates positively with the likelihood of technological innovation by steel manufacturers and scrap recyclers, as well as with the propensity for green consumption by construction firms. However, as the cost differential surpasses a certain threshold, the positive correlation between the probability of green consumption by construction firms and the production cost differential inverts to a negative one. This suggests that the increased product price, stemming from higher costs, ultimately affects the net income of construction firms, prompting a strategic shift. Consequently, it is imperative for the government to bolster regulatory and economic support for enterprises, particularly when their capacity for technological innovation is low (Shi et al., 2023).

(2) The second most influential factor is the carbon returns (S_c) derived from technological innovation by steel manufacturers. With the carbon trading market as the primary source of carbon revenue, the commodification of carbon emissions can serve as a potent catalyst for manufacturers to enhance production efficiency and engage in technological innovation (Fang et al., 2023; Wang et al., 2023). While existing literature has examined the impact of carbon trading on corporate technological innovation (Jia et al., 2024), it has neglected the effects of carbon benefits on stakeholders post-implementation of carbon trading. From an evolutionary game perspective, our study reveals that steel manufacturers are inclined to innovate technologically as carbon benefits escalate.

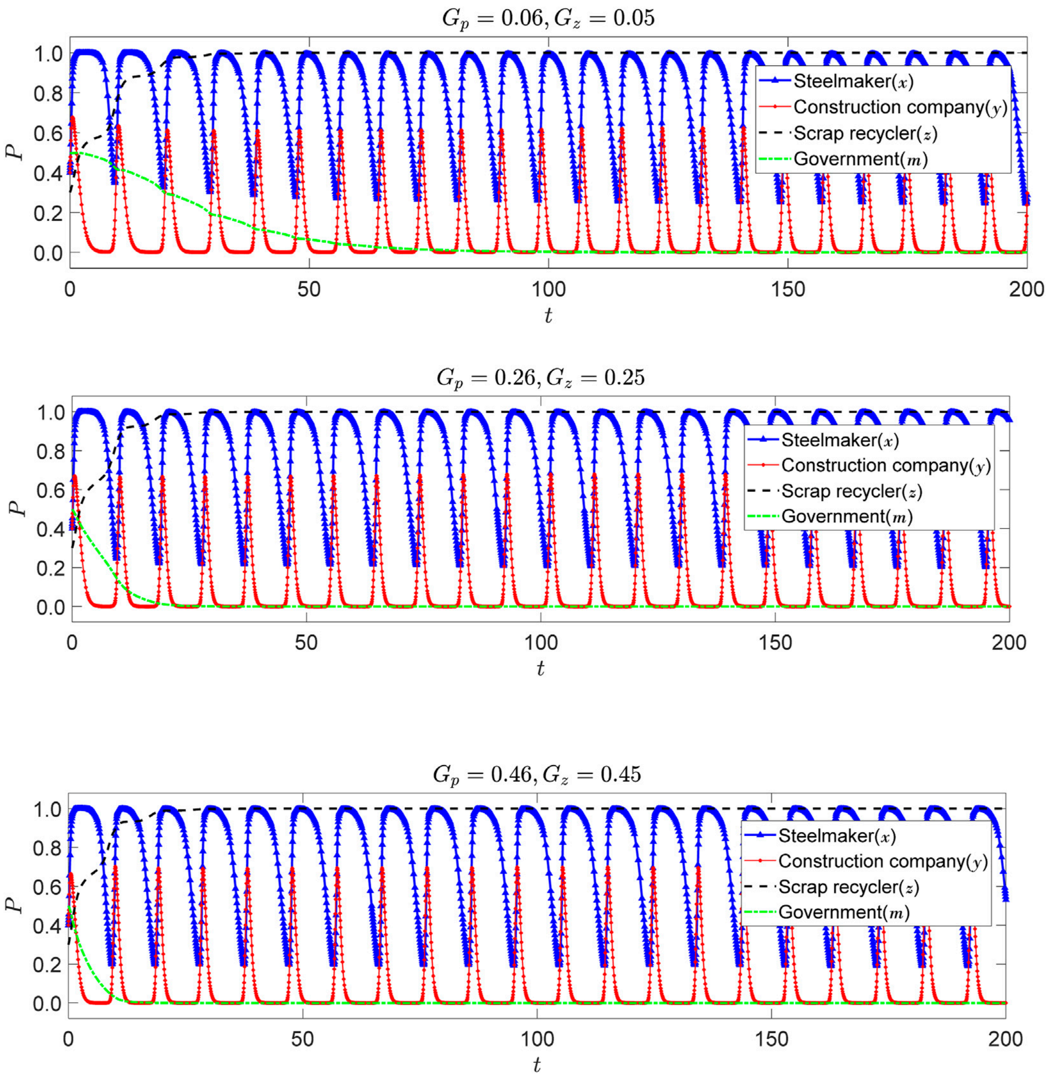

FIGURE 14
Effect of G_p, G_z on system evolution.

Furthermore, the escalation of carbon benefits leads to increased production costs and product prices for steel manufacturers, which in turn prompts construction companies to prefer traditional consumption patterns.

(3) The impact of government consumption subsidies ranks third in significance, with the probability of technological innovation by steel manufacturers and scrap recyclers being positively correlated with these subsidies. Generally, the likelihood of green consumption by construction firms is also positively correlated with consumption subsidies. The least influential factors, though still impactful to some degree, include subsidies for technological innovation, processing costs for steel scrap recyclers, and government credibility. Research has indicated that in the nascent stages of technological innovation, governments often extend incentive subsidies to manufacturers to foster innovation (Xu et al., 2024). Conversely, in the later stages, they tend to offer direct subsidies to consumers to promote market acceptance and widespread adoption of innovative products. Our study confirms that this pattern holds in the steel industry, where the potential benefits of both technological innovation subsidies and consumer subsidies influence the government's subsidy decisions. As the government's technological innovation subsidies escalate, there is a preference for implementing consumption subsidies, with the likelihood of offering technological innovation subsidies gradually diminishing. The government must rationally adjust the form of subsidies based on its interests. Moreover, as government credibility strengthens, the probability of green consumption by construction enterprises initially increases and then follows a decreasing trend, indicating a waning incentive effect of consumption subsidies over time.

(4) Lastly, the processing cost differential before and after technological innovation by scrap steel recyclers merits attention. While previous studies have established a

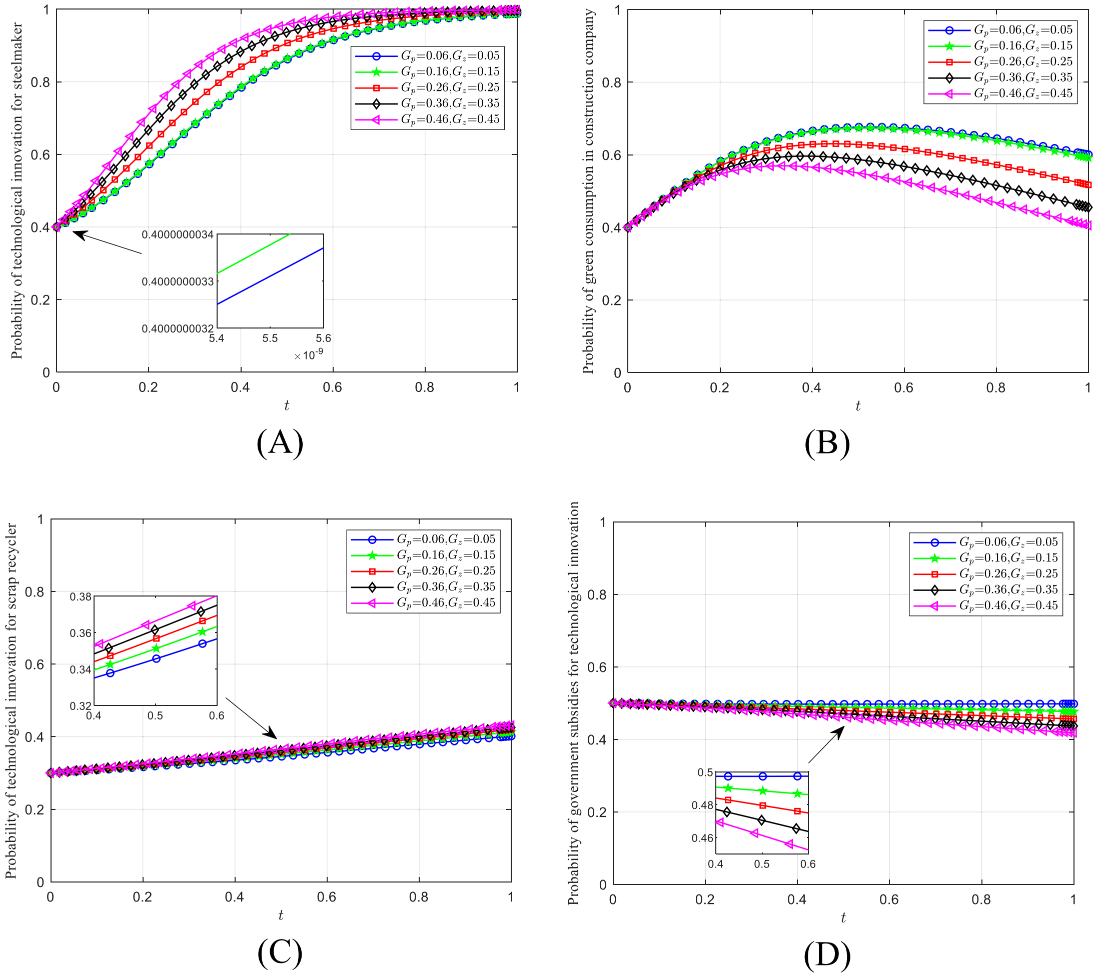

FIGURE 15
(A–D) Impact of G_p and G_z on quadrilateral subjects.

tripartite evolutionary game model involving large steel enterprises, small and medium-sized steel enterprises, and the government to explore synergistic emission reduction (Tian et al., 2024), our study broadens this perspective by incorporating scrap recyclers into the game model, thereby enriching the research findings in this domain. We conclude that an increasing processing cost differential $(C_{r2} - C_{r1})$ significantly reduces the probability of technological innovation by scrap recyclers. Processing costs are a pivotal factor influencing their technological innovation, and government subsidies can effectively incentivize the low-carbon transition of scrap recyclers.

6.2 Policy implications

Through comprehensive analysis, this study delineates the future trajectory for carbon reduction in the steel industry, which involves technological innovation by steel manufacturers and scrap steel recyclers, green consumption by downstream construction enterprises, and the implementation of technological innovation subsidies by the government. Building on the deductions from the previous text, this paper proposes policy recommendations for carbon reduction in the production, consumption, and recycling processes of steel.

To alleviate the pressure on steel manufacturers to transition to low-carbon practices, the government should provide reasonable subsidies to inject new momentum into their technological innovation. Green technological innovation is crucial for addressing environmental pollution and achieving sustainable development. However, steel manufacturers often face significant upfront costs and slow returns on investment when engaging in green technological innovation. Despite these challenges, such innovation is essential for the transformation and competitive edge of steel manufacturers. Therefore, the government must offer financial support through technological innovation subsidies to enhance their motivation for green technological innovation. As low-carbon metallurgical technologies advance, steel manufacturing processes will undergo revolutionary changes. Steel manufacturers need to recognize the situation, accelerate high-quality development, improve green technological innovation levels, and reduce pollutant emissions. They should intensify research and development in cutting-edge metallurgical technologies, adopt innovative development concepts, transform resources into valuable assets,

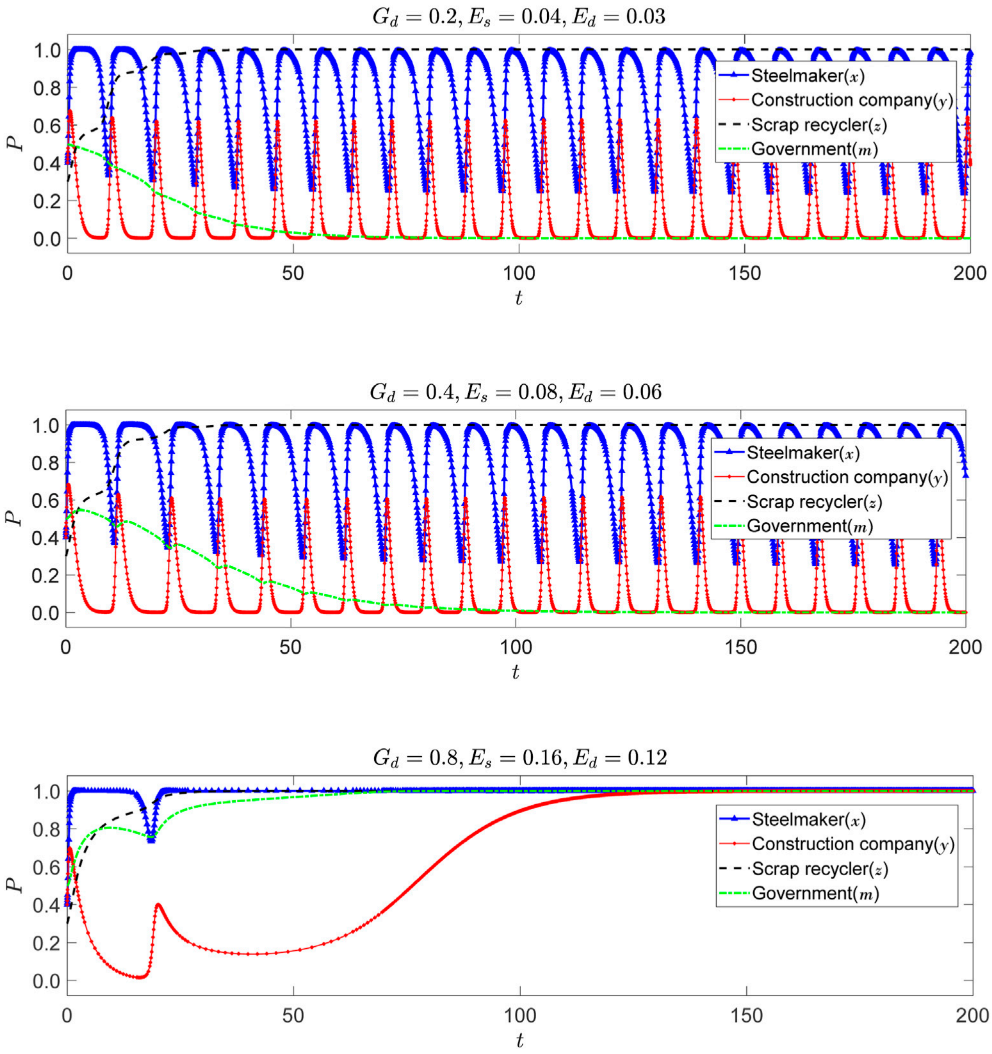

FIGURE 16
Effect of G_d, E_s and E_d on system evolution.

enhance resource utilization, and gradually resolve environmental pollution issues.

Encouraging Green Consumption in Downstream Construction Enterprises. The consumption behavior of construction enterprises directly impacts the production methods of steel manufacturers. Their preference for green products can compel steel manufacturers to innovate technologically. The government should maintain a certain level of consumption subsidies to encourage construction enterprises to purchase green products. Additionally, relevant departments should leverage new media platforms to promote the concept of green consumption in the construction sector, gradually encouraging construction enterprises to prioritize green and low-carbon products. The government should strengthen regulation of enterprises, promote green certification of low-carbon products, and encourage the use of credible environmental labels to bolster the resolve of construction enterprises to purchase green products. For construction enterprises, it is advisable to use Building Information Modeling (BIM) technology in the design phase to optimize steel usage, reduce waste from over-purchasing and cutting. During construction, they should use high-precision cutting tools and technologies to ensure accurate steel cutting and minimize leftover waste. It is also essential to enhance on-site management to prevent waste and loss due to improper storage. Finally, establishing cooperative relationships with local scrap steel recyclers ensures that steel from construction waste can be effectively recycled and reused.

Enhancing the Viability and Competitiveness of Scrap Steel Recyclers. The strategic choices of scrap steel recyclers are influenced by their processing costs. While ensuring the normal profit margins of scrap steel recyclers, the government should provide technological innovation subsidies and consumption subsidies to foster healthy competition among recyclers. Large-scale recyclers, due to their substantial business volume, require significant capital, and government departments should increase financial support for scrap steel recyclers. Scrap steel recyclers themselves should gradually establish a comprehensive recycling

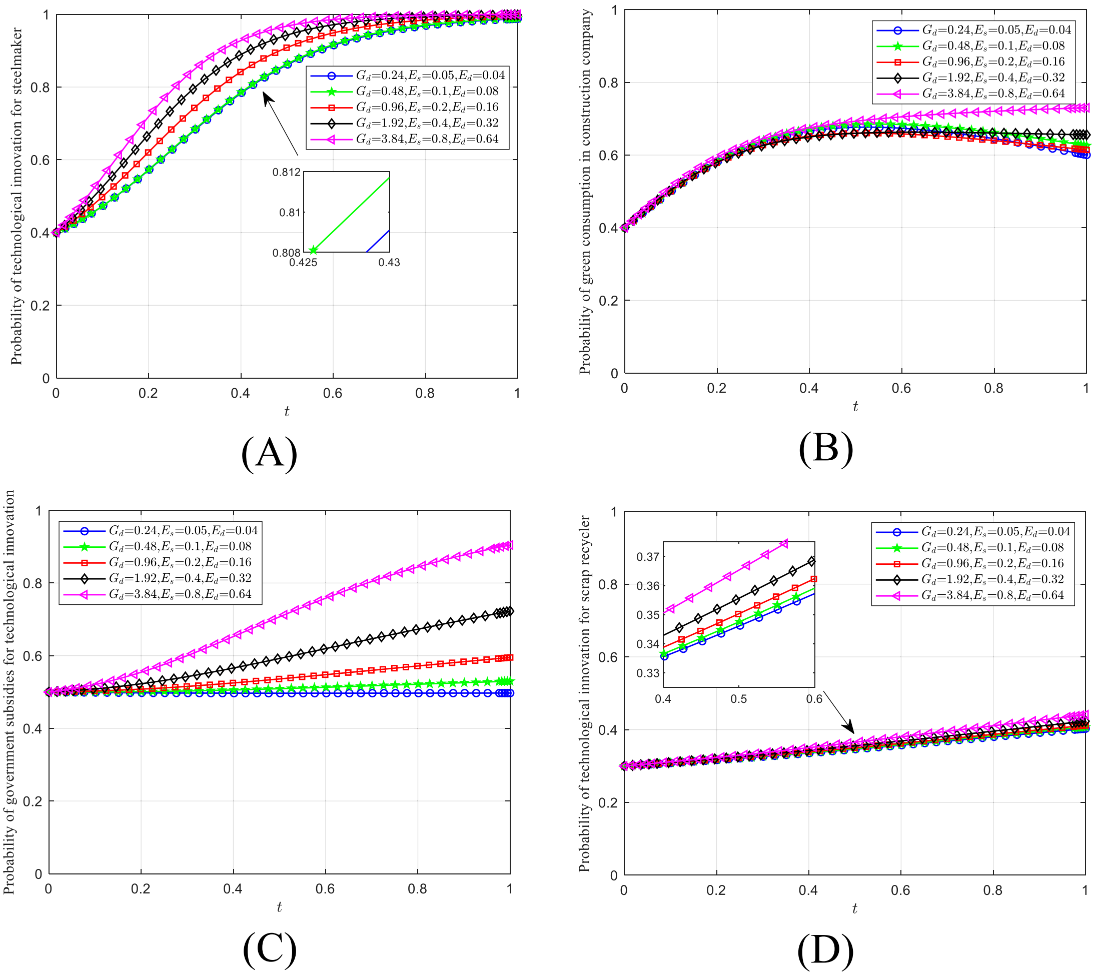

FIGURE 17
(A–D) Impact of G_d, E_s and E_d on quadrilateral subjects.

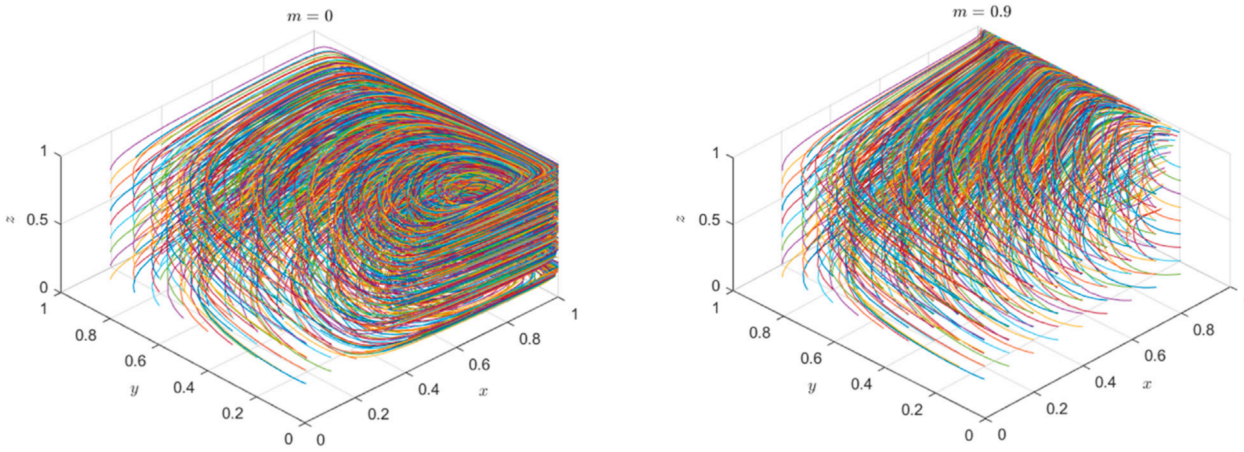

FIGURE 18
Impact of government subsidy mechanisms on the evolution of parties' strategies.

supply network, promote the scaled and clustered development of the scrap steel industry, and continuously establish new types of scrap steel recycling bases that integrate collection, sorting, processing, and distribution in various regions. By leveraging scaled operations, they can enhance market competitiveness. Additionally, scrap steel recyclers should take advantage of government support to actively optimize production processes and equipment through technological innovation, improve the efficiency of scrap steel recovery and reprocessing, reduce the waste of materials and energy, and achieve the maximum carbon reduction goals at the recycling stage, contributing to the low-carbon and high-quality development of the economy and society.

Strengthening Coordination in Carbon Reduction Across the Steel Production, Consumption, and Recycling Processes. The government, with different interests in implementing technological innovation subsidies and consumption subsidies, has its strategic choices influenced by the strategies of steel manufacturers, construction enterprises, and scrap steel recyclers. As the linchpin of the system, the government should reasonably arrange subsidies and regulate the amount and timing of subsidies. Moreover, the government can also implement a dynamic subsidy system based on the state of social development and the different stages of the low-carbon transition of the steel industry. The study found that the carbon benefits from technological innovation by steel manufacturers are the second most sensitive factor. Therefore, it is crucial for the government to continuously improve carbon emission standards and quotas for the steel industry and integrate them into the legal and regulatory framework. This includes clearly defining the carbon emission requirements that steel manufacturers must adhere to during their production and operational processes, as well as the corresponding punitive measures and penalty mechanisms. Furthermore, the carbon emission quota trading mechanism in the steel industry is not yet mature, and the government must strengthen guidance to encourage voluntary emission reductions by steel manufacturers, enhancing the efficiency of carbon emission management and control. This will promote technological innovation and optimize production processes to reduce carbon emission levels.

7 Conclusion

This study, for the first time, introduces the four-player Evolutionary Game Theory (EGT) into the carbon reduction system of the steel industry, encompassing the cyclical processes of production, consumption, and recycling. The paper not only extends the application scope of EGT but also enriches existing research on carbon reduction in the steel industry, offering targeted policy recommendations for all stakeholders. Unlike previous studies, this paper focuses on finding an equilibrium of interests among the system's entities under government subsidies, an aspect that has not been thoroughly considered in prior research. The main conclusions are as follows.

(1) This study affirms the critical role of government subsidies in fostering technological innovation among steel manufacturers. Well-targeted subsidies can catalyze low-carbon production processes, which are pivotal for steering the steel industry towards a sustainable and eco-friendly future. Consequently, it is imperative for the government to persist in refining and enhancing policies that subsidize technological innovation within the steel sector. This will not only stimulate technological advancement and innovation for low-carbon production but also ensure the industry's long-term viability and competitiveness.
(2) The strategic decisions regarding technological innovation made by steel manufacturers and scrap recyclers are predominantly cost-driven. Subsidies aimed at technological innovation can mitigate a portion of these costs, thereby offering a compelling incentive for embracing low-carbon transformation. It is advisable for the government to contemplate offering increased financial assistance and tax relief to alleviate the financial strain associated with technological innovation. This approach would encourage the adoption of more environmentally conscious and efficient production methods.
(3) The carbon benefits derived from technological innovation for steel manufacturers are a significant motivating factor. If steel manufacturers stand to gain from environmental regulations, their likelihood of engaging in technological innovation is substantially heightened. This underscores the importance of refining the carbon trading mechanism within the steel industry. The government is encouraged to enhance this mechanism to motivate businesses to decrease carbon emissions through market-based strategies. Additionally, providing financial incentives or subsidies to businesses for carbon reduction efforts could foster a synergistic relationship between technological innovation and environmental regulation.
(4) The strategies employed by construction companies may be influenced by the production costs and carbon returns of steel manufacturers. There is a positive correlation between the carbon gains of steel manufacturers and the green purchasing tendencies of construction enterprises. When the disparity in production costs for steel manufacturers surpasses a certain threshold, construction enterprises tend to revert to traditional consumption patterns. Therefore, it is recommended that the government and industry bodies collaborate to boost demand for green building materials within the construction sector. Efforts should be made to incentivize construction firms to adopt green materials and low-carbon technologies through the establishment of green building standards and certification programs.

This paper endeavors to offer a set of constructive suggestions to address the complexities of carbon emission reduction in the iron and steel industry. However, it acknowledges its own limitations and suggests that further research is necessary to enhance the understanding of this intricate system. While this study has taken into account 21 factors, it has primarily focused on a subset of key parameters. The technological innovation within the broader context of carbon emission reduction is indeed a multifaceted issue, and there is scope for incorporating additional parameters to achieve a more holistic analysis. Considering the involvement of stakeholders such as the upstream companies of steel manufacturers in the carbon emission lifecycle of the steel industry, it would be beneficial to expand the scope of this research to include these entities. This would provide a more comprehensive view of the carbon emissions across the entire steel life cycle. Furthermore, given the close interconnection between scrap recyclers and steel manufacturers, exploring the potential of merging these two entities within the model could simplify the analysis while still capturing the essential dynamics. This approach merits consideration as a valuable direction for future studies aiming to refine and expand upon the current research.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TX: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. LS: Data curation, Formal Analysis, Software, Validation, Writing–original draft, Writing–review and editing. WGY: Writing–original draft, Writing–review and editing. WY: Writing–original draft, Writing–review and editing. MD: Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

First and foremost, we extend our deepest gratitude to everyone who has contributed to the crafting of this manuscript. Our sincere appreciation also goes to the Jiangxi Provincial Department of Education for their generous financial backing through the Science and Technology Research Project (Project No. GJJ2201327) and the Provincial Project on Teaching Reform Research in Higher Education Institutions in Jiangxi Province (Project No. JXJG-21-10-2). Lastly, we are immensely thankful to the esteemed readers who, amidst their hectic schedules, have taken the time to review this thesis. Their valuable insights are certain to significantly enhance our future academic endeavors.

Conflict of interest

Author WGY was employed by State Grid Jiangxi Electric power Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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