

Research on the Advanced and Applicable Technical Path of Steel based on the Evolution Game of Public Goods

Haoyu Guo^{+, a}, Jiawen Li^{+, b}, Jinghua Zhang^{+, c}, Yuhan Chen^{+, d}, Danping Wang^{e, *}

North China University of Science and Technology, Tangshan 063210, China

^a15633300378@163.com, ^b1794143651@qq.com, ^czjh0030505@126.com,
^d3426603019@qq.com, ^{e,*}danping@ncst.edu.cn

Abstract

In this paper, we discuss that under the background of carbon emission quota, with advanced applicable technology as the participant of the evolutionary game, taking carbon emission quota as the resource threshold, setting the benefit function of advanced technology and adopting the Fermi strategy updating rule, Monte Carlo simulation is conducted to achieve the game objective of minimizing the total cost and maximizing the carbon emission reduction effect, and numerical simulation is used to verify the model. The results show that: (1) Carbon emission quotas are crucial to promote technological upgrading of iron and steel enterprises to achieve the reduction of steel carbon emissions; (2) Moderately increasing the synergy factor can effectively enhance the cooperation level of advanced application technologies.

Keywords

Carbon Emission Allowances; Monte Carlo Simulation; Public Goods Evolution Game.

1. Introduction

As the most critical challenge and systemic hazard facing the world in the 21st century, global warming is becoming increasingly serious, with global fossil fuel CO₂ emissions reaching 37.86 Gt in 2021^[1]. The Fifth Assessment Report of the IPCC clearly points out that climate change is caused by anthropogenic greenhouse gas emissions, and that, as a major greenhouse gas, excessive CO₂ emissions contribute to global warming, posing a major threat to the sustainable development of humankind^[2]. This poses a major threat to sustainable human development. In order to achieve the Paris Agreement's goal of limiting global temperature rise to below 2 °C^[3], China has actively assumed the responsibility of a major country by committing itself to realizing the peaking of CO₂ emissions by 2030 and achieving carbon neutrality by 2060.

China has become the world's largest steel producer^[4]. The scale of steel production in China has been expanding, with crude steel production increasing from 128 metric tons in 2000 to 1,060 metric tons in 2020, and its share of world production increasing from 15% to 56%^[5]. At the same time, the iron and steel industry accounts for about 15% of China's CO₂ emissions. In order to realize China's dual-carbon goal, the iron and steel industry will face a huge challenge in its carbon reduction efforts. Therefore, it is imperative to explore carbon neutral pathways for China's steel industry. Currently, the iron and steel industry has explored a variety of carbon reduction technologies, such as improving energy efficiency, transforming production structure, energy-saving technological transformation, fuel switching, hydrogen steel-making, and CCUS (Carbon Capture, Utilization and Storage)^[7]. And because the production process of China's iron and steel industry mainly includes long process and short process. In the long process, iron ore and coal are used to produce steel products after procedures such as sintering, coking, iron-making, steel-making and rolling. In the short process, there are only

two procedures: electric arc furnace steel-making and steel rolling, these technologies, although to a certain extent, reduce CO₂ emissions, but different advanced and applicable technologies in different processes will produce different effects, different emission reduction technologies on the use of raw materials have different impacts, for example, to change the structure of the production, if the use of the blast furnace to alkaline oxygen furnace and then to the electric arc furnace production, it will reduce the mining of iron ore but increase the demand for scrap; if the development of non-blast furnace iron-making technology and then increase the demand for scrap; if the development of non-blast furnace iron-making technology and then the development of non-blast furnace iron-making technology, the development of iron ore and coal production^[8]. The development of non-blast furnace iron-making technology will increase the use of iron ore. Therefore, this paper focuses on the research of advanced and applicable technologies for the long process of iron and steel smelting.

At the same time, China's iron and steel industry carbon emission quota trading market has officially entered the start-up stage, carbon emission quota trading accelerates the clearing of backward production capacity by incentivizing the advanced and restraining the backward, and promotes the iron and steel smelting from the traditional path to the low-carbon competitiveness of applying the advanced and applicable technology of the new track to change, and accelerates the low-carbon technological innovation and application. Therefore, under the background of carbon emission quota trading in the iron and steel industry, optimizing iron and steel smelting technology, researching iron and steel smelting carbon emission reduction technology path, and selecting advanced and applicable technologies are of great significance for the iron and steel industry to achieve the goal of carbon neutrality.

Evolutionary game theory is developed from biology^[9], which effectively and reasonably solves the problem that has long plagued scholars since Darwin - how cooperation is generated and maintained. As an indispensable mathematical model, evolutionary games can correctly characterize the game behavior of individuals in a population and predict the evolutionary outcomes in different situations. The main research contents of evolutionary games include four aspects: game model, strategy updating rules, population structure and evolutionary outcomes. The core of the game model is the payoff matrix or payoff function. The strategy updating rule determines how individuals update their strategies according to the payoff function. In order to study and solve the problem of choosing advanced technologies in the long process of iron and steel smelting, the evolutionary game investigates the strategy updating process considering the external environment and internal drivers, thus providing new ideas and solutions on how to promote cooperation in cooperative dilemmas.

In this paper, under the background of carbon emission quota in iron and steel smelting, the evolutionary game model of public goods is established, and the benefit function is derived by combining with the classical game model, and the advanced and applicable technologies in iron and steel smelting are classified into five major processes, namely, coking, sintering, blast furnace, converter, and rolling, according to the processes as the network structure of the evolutionary game. According to the benefit function of the advanced and applicable technologies, the strategies of the advanced technologies are updated through Monte Carlo simulation according to the Fermi principle. Combining the carbon quota of iron and steel smelting with the evolutionary game model, the sensitivity of parameter regulation to the advanced and applicable technologies of iron and steel smelting is analyzed through numerical simulation, and some suggestions for the selection of advanced and applicable technologies are given.

2. Methodology

Evolutionary game models can be used for dynamic analysis of biological evolution, economic competition, technology diffusion, and social behavior and strategies. Evolutionary game theory can be applied to the decision-making analysis of iron and steel smelting technology, the carbon quota trading as a penalty for advanced technology evolutionary game^[11], to discuss in the context of carbon

quota trading iron and steel enterprises to choose the iron and steel smelting carbon emission reduction of the most coordinated investment strategy of advanced technology^[6].

A public goods evolutionary game model is constructed to analyze how steel smelting advanced technologies make strategic choices under the carbon quota trading market environment. The participants of the model are the advanced and applicable technologies in the five major processes of iron and steel smelting: coking, sintering, iron-making, steel-making and steel rolling. The general idea of the model study is shown in the figure below:

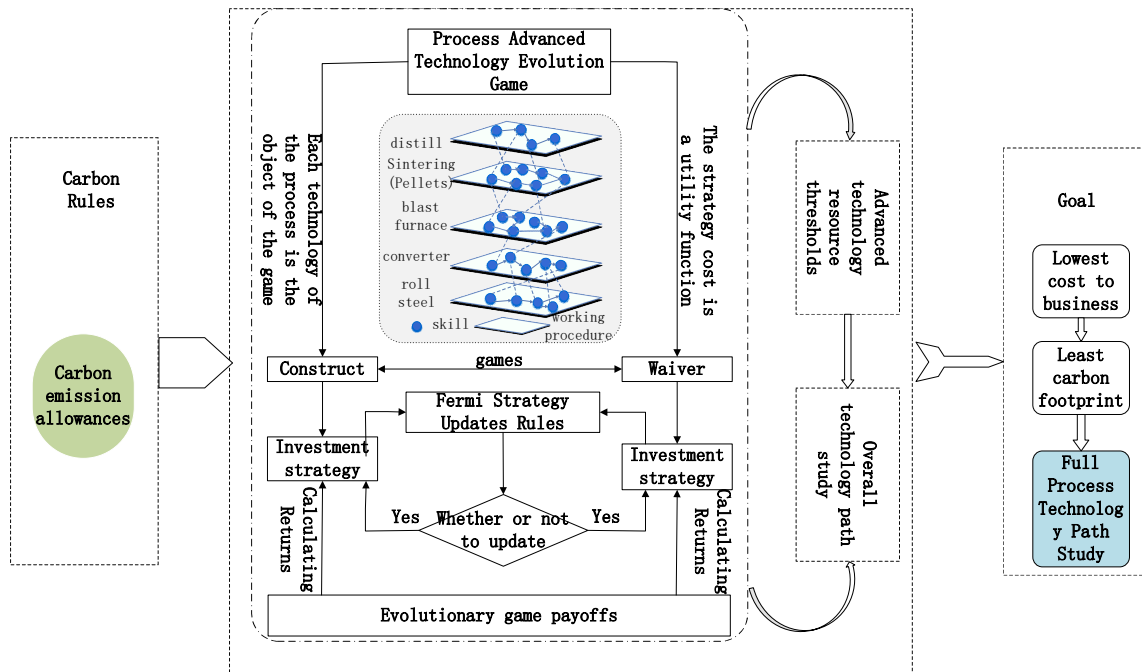


Figure 1. General idea of the modeling study

2.1 Underlying Assumption

Advanced technology groups are finite in size and more stochastic in small groups, which may produce different evolutionary outcomes than infinite groups. Advanced technology groups are structured, with individuals interacting only with their neighbors, and spatial structure significantly affects cooperative evolution. Groups of advanced technology individuals have different investment costs, profits, and carbon-reducing capacities, leading to different contribution capacities.

Cooperation (C): paying cost c to contribute resources to the common pool, with contribution in the interval $[0, C_{max}]$. Betrayal (D)^[16]: no cost, but public good benefits, with penalties for potentially exceeding carbon reduction thresholds. Individuals switch strategies with a certain probability according to the Fermi rule by comparing their own benefits with those of their neighbors^[12].

Individuals are not able to optimize globally, but only adjust their strategies based on local information (e.g., neighbors' benefits). Individuals can accurately perceive others' contributions or the total amount of public goods allowing individuals to adjust their strategies based on historical interactions (e.g., reinforcement learning). Remaining state-of-the-art individuals cannot prevent non-contributors from enjoying the public good-emission CO₂.

With a penalty mechanism that imposes a cost on the betrayer, taking into account the cost of monitoring; and a reward mechanism that provides additional incentives (e.g., carbon allowances) to those who cooperate. and with resource constraints for steel smelting at risk of exceeding carbon emission thresholds promote cooperation through a multi-process evolutionary game, in contrast to the assumption of a single game.

2.2 Advanced Appropriate Technology Network Architecture

The structure of the evolutionary game network for advanced applicable technologies is shown in Fig.

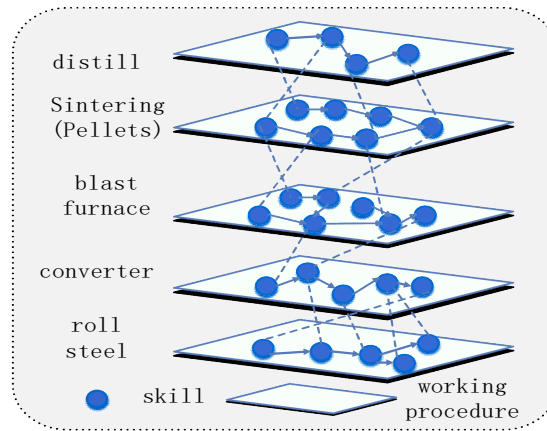


Figure 2. Evolutionary gaming network structures for advanced and applicable technologies

The advanced and applicable technologies in iron and steel smelting are divided into five major processes, namely coking, sintering, blast furnace, converter and steel rolling, as the network structure of the evolution game. The nodes of advanced technologies in one layer of processes contain G technologies in each round of the game, and the G nodes of each process correspond to the participants of the game. At the same time if the advanced applicable technology in different processes if there is synergy, then the two layers of processes will produce the same strategy choice.

2.3 A Game Model of Public Goods Evolution Based on Carbon Emission Allowances

As a typical game model, the public goods game is widely used in solving the problem of group conflict of interest^[10]. Each layer of advanced and applicable technology is abstracted as a node, and the strategy space of the node is [Cooperation (C), Betrayal (D)]. In each round of the game, the cooperator C contributes the amount of investment in advanced technology c , the betrayer D strategy is not to choose to use this advanced technology, additional provisions to reduce carbon emissions play a role in the advanced technology for the punisher P, the punisher of the betrayer to impose the intensity of the punishment for a in order to promote the advanced technology to update the iteration of the penalty strength of the iron and steel smelting of the carbon reduction quota decision.

Step 1: Setting the strategy benefit function

The benefit of the advanced applicable technology is the sum of the node's benefits as focus and neighbor A respectively.^[16]

$$\Theta_i = \sum_i^G \Delta_i^L \quad (1)$$

Where: i denotes a particular advanced technology; G denotes all advanced technologies in a process layer.

Focus A gain: Advanced technology A is selected as the focus, other advanced technologies with the same process as the focus are the neighbors, and A plays an evolutionary game with the focus technology A. The gain of the focus technology A is as follows:

$$\Delta_i^{l=i} = \frac{r \times N_C}{G} - c_i \quad (2)$$

where $\Delta_i^{l=1}$ denotes the benefit of the focal advanced technology A, N_c denotes the number of cooperators in the G population under the evolutionary game, and c_i denotes the fixed contribution of the focal technology A. The number of neighbors in the G population is the number of neighbors in the G population under the evolutionary game. $c_i = c$ if A is a cooperator, and $c_i = 0$ otherwise. L denotes the total number of neighbors including A.

Neighbor A Gain Selects advanced technology A as a neighbor, advanced technology A as a neighbor participates in the advanced technology evolution game with other neighbors as focuses, and advanced technology A as a neighbor gains from the evolution game:

$$\Delta_i^{l=L-1} = \frac{r \times N_c}{G} - c_i \tag{3}$$

Set the carbon emission reduction quota threshold^[17]. If the contributed carbon emission reduction exceeds the carbon emission reduction quota threshold in a round of the game, the contributed resources are equally distributed to each individual; if the contributed carbon emission reduction does not exceed the threshold, the resources are divided into two parts, the first part is less than the threshold, and the contributed resources are equally distributed to each individual; the second part, the part that exceeds the carbon emission quota \times the carbon trading price, is used as a reward overhang in accordance with each individual's strategic choice with a certain weighting The second part, the part exceeding the carbon emission quota \times carbon trading price, is rewarded to each individual with a certain weight according to the strategy choice of each individual.

Step 2: Setting up the calculation process

System initialization: the initial strategy of each technology is randomly arranged and the distribution conforms to uniform distribution.

Step I: Assign numbers to all technologies in the process and determine the neighbors of the focal individual and the focal technology, the following table is an example of the numbering of a layer of processes

Table 1. Number and Example

neighbors	Technical name	serial number	Technical Brief
distill	High temperature and high pressure dry coke quenching technology	CQT	Reduction of energy consumption by 5 kgce/t-coke
	Coke Oven Rising Tube Desert Gas Waste Heat Recovery Technology with High Efficiency	RIS	Reduction of energy consumption by more than 7kgce/t-joule
	Coke Oven Circulating Ammonia Waste Heat Recovery	FL	Reduces energy consumption by 0.5-1kgce/t-joule
	Coke oven charring chamber waste gas recovery and automatic pressure regulation technology	COY ₁	Reduction of energy consumption by 2~4kgce/t-joule
	Energy-saving Coke Oven Covers	COY ₂	Reduce energy consumption by 0.5~1kgce/t-joule
	Coke Oven Automatic Heating Control Technology	COY ₃	Annual CO ₂ emission reduction of 160,000 tons

Step II: Based on the node total revenue formula, calculate the total revenue of the selected technology i. Randomly select a certain neighbor of technology i as j. Based on Fermi's rule, the advanced technology j mimics the strategy of its neighbor j with a certain probability, and the mimicry probability is shown as follows:

$$Pr ob(s_i < s_j) = \frac{1}{1 + e^{\Theta_i - \Theta_j} / k} \quad (4)$$

where: Θ_i and Θ_j are the total revenues of advanced technology i and advanced technology j, respectively. k denotes the ambient noise or intensity of the strategy selection, and the strategy selection becomes more and more irrational as k increases, with k specified to be set at 0.5;

Step III: Steps 1 and 2 are repeated $G \times G$ in a round of Monte Carlo simulation, and then run again from system initialization until an evolutionary steady state is reached.^[18]

Step 3: Setting the strategy evolutionary steady state

The evolutionary steady state is the state in which the developmental technology strategy no longer changes frequently, and tends to stabilize the cooperation strategy at a certain stable level, and the system strategy evolution tends to converge. In this paper, the goal of the model is to minimize the total cost and maximize the effect of carbon emission reduction, set the model to achieve evolutionary stability needs to meet the total cost minimization and maximize the effect of carbon emission reduction^[13].

The cost of applying advanced technology in one layer of process includes initial investment cost, maintenance cost and operation cost. The evolutionary stability of the model strategy requires that the following equation meets the set threshold value

$$opt. \begin{cases} \min TC = \sum_{i=1}^T (IC_i + OMC_i) \\ \max CE = \sum_{i=1}^T \sum_{t=1}^{T_i} \delta_{i,t} \end{cases} \quad (5)$$

Where: TC denotes the total cost of the iron and steel smelting process; IC_i is the investment cost of the advanced technology t; OMC_i denotes the maintenance and operation cost of the equipment where the advanced technology i is located; $\delta_{i,t}$ is the reduction of carbon dioxide emission of the advanced technology i in the year t; CE denotes the total amount of carbon emission reduction of the iron and steel smelting process using the advanced technology.^[19]

$$IC_i = C_i \times X_i \times \frac{R(1+R)^{T_i}}{(1+R)^{T_i} - 1} \quad (6)$$

Where C_i represents the initial investment cost of advanced technology i per unit of capacity, including the sum of construction costs, equipment costs and installation costs, and other initial investments required for the use of advanced technology; X_i represents the production capacity of equipment i; R represents the internal rate of return of the iron and steel industry; and T_i represents the service life of equipment i using advanced technology.

$$OMC_i = \sum_{i=1}^{T_i} P_{i,t}^o \times S_{i,t} \times \lambda_{i,t} \quad (7)$$

Where $p_{i,t}^o$ denotes the maintenance cost per unit of production capacity of advanced technology i in year t ; $S_{i,t}$ denotes the actual operating capacity of advanced technology i in year t ; and $\lambda_{i,t}$ denotes the operating rate of advanced technology i in year t .^[20]

3. Data Simulation Analysis

The data and cost aspects of advanced steel smelting technologies in this paper are obtained through simulation. The following figure shows the simulation results of the influence of evolutionary games obtained through simulated data. However, when the carbon quota value and the synergy factor are fixed, the cooperation ratio of advanced technologies increases as the evolutionary game progresses. Meanwhile, in the early stage of the evolutionary game, the cumulative emission reduction volume keeps changing. Through simulation, advanced steel smelting technologies show that the total cost remains stable, and ultimately the carbon reduction cost and the cumulative emission reduction volume maintain a dynamic balance.

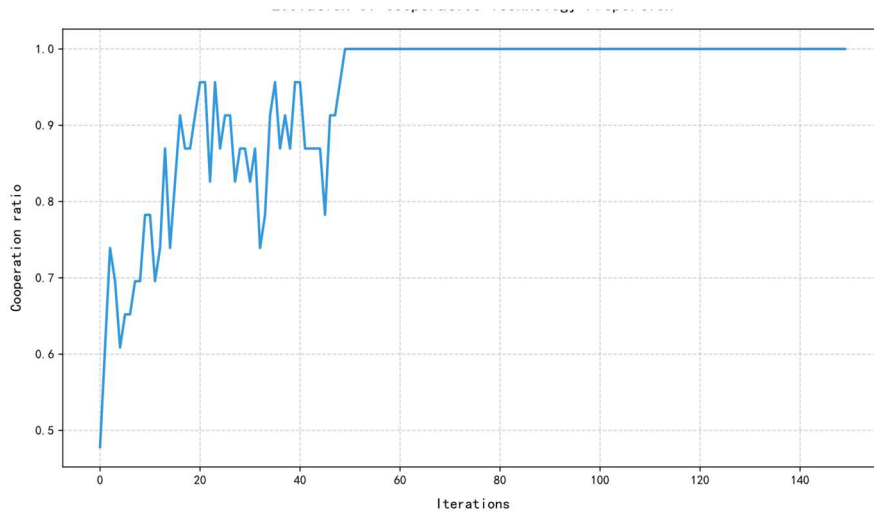


Figure 3. Evolution of the proportion of cooperative

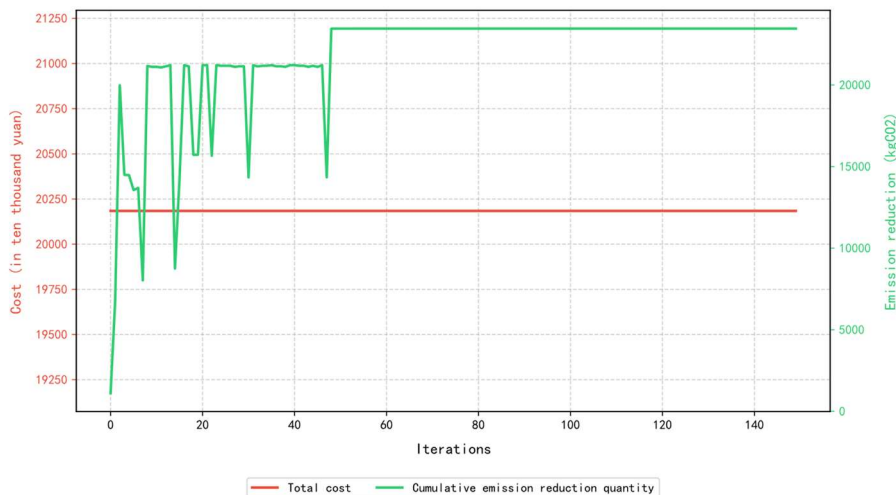


Figure 4. Cost-abatement dynamic equilibrium diagram

When the model only uses the carbon emission quota as the incentive measure for the resource threshold, the proportion of cooperators is in a growing trend, and the proportion of cooperators stabilizes around 0.9 in the late stage of evolution^[14]; when the model of the evolutionary game uses the carbon emission quota as the resource threshold, and if the contribution of carbon emission reduction exceeds the threshold of the carbon emission reduction in one round of the game, the contributed resources are distributed equally to each individual, and at the same time, the technology that adopts the strategy of betrayal is punished, the proportion of cooperators in the model grows slower, but the proportion of cooperators increases slowly. grows at a slower rate, but the upper limit of the proportion of cooperators is higher than the case where only the punishment of frustration is taken.

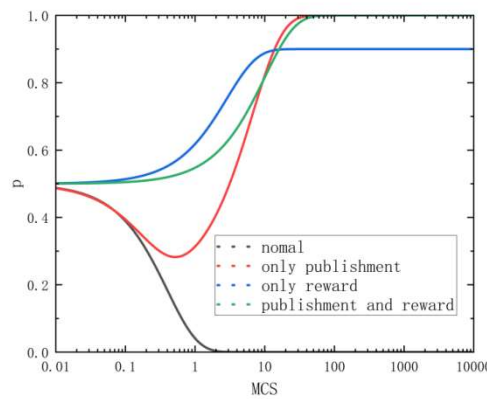


Figure 5. Simulation diagram of the evolutionary game model

Further analyze the synergy effect of different enhancement factors on the cooperation strategy for the selection of advanced and applicable technologies when the resource threshold of carbon emissions remains unchanged. The proportion of the cooperation level P is strongly influenced by the synergy factor. The figure shows that the proportion of the cooperation level changes with the variation of the synergy factor. By fixing the resource threshold, when the value of r jumps from 3 to 3.5, it can increase from 0 to 83.9%. Furthermore, as the value of the synergy factor increases, the cooperation ratio becomes more sensitive to R . The larger the value of the synergy factor, the faster the growth rate of the cooperation ratio, and the synergy factor will significantly affect the cooperation level flat.

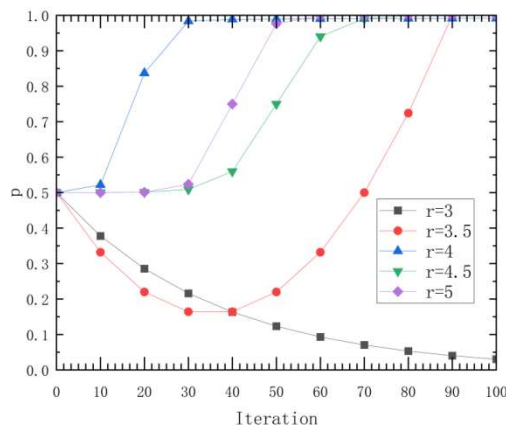


Figure 6. The influence of synergy factors on the proportion of cooperation

4. Conclusion

When the evolutionary game model takes carbon emission quotas as the resource threshold, rewards the contribution of carbon emission reduction exceeding the carbon emission reduction threshold, and punishes the technologies that adopt betrayal strategies with the portion not exceeding it as a penalty measure, the cooperation proportion of advanced and applicable technologies is high and the growth rate is fast. Carbon emission quotas play an important role in promoting technological renewal and upgrading in the steel industry. Meanwhile, when the synergy factor $R > 3$, the advanced and applicable technologies adopting the cooperation strategy can survive. However, when $R > 3.5$, the cooperation ratio first increases and then decreases, which has a synergy effect of punishment and reward. Moreover, the carbon emission quota threshold can promote the increase of the cooperation ratio and suppress the phenomenon of insufficient evolutionary game caused by the increase of the synergy factor.

Acknowledgments

This work is funded by the Research Project of the Innovation and Entrepreneurship Training Program for College Students of North China University of Science and Technology, Project Number: S202410081150.

References

- [1] CO2 Emissions of All World Countries - 2022 Report on <https://www.iea.org>.
- [2] Climate change 2013: the physical science basis: working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change on <https://archive.ipcc.ch>.
- [3] Meinshausen, M., Lewis, J., McGlade, C. et al. Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature* 604, 304–309 (2022).
- [4] Steel statistical yearbooks 2021 on <https://worldsteel.org>.
- [5] Runying An, Biying Yu, Ru Li, Yi-Ming Wei, Potential of energy savings and CO2 emission reduction in China's iron and steel industry, *Applied Energy*, Volume 226, 2018, Pages 862-880.
- [6] Chao Zhang, Xinxin Zhang, Evolutionary game analysis of air pollution co-investment in emission reductions by steel enterprises under carbon quota trading mechanism, *Journal of Environmental Management*, Volume 317, 2022, 115376.
- [7] Lei Ren, Sheng Zhou, Tianduo Peng, Xunmin Ou, A review of CO2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China, *Renewable and Sustainable Energy Reviews*, Volume 143, 2021, 110846.
- [8] Technology Transformation Paths in the Steel Industry. <https://transitionasia.org>.
- [9] Nowak MA. Five rules for the evolution of cooperation. *Science*. 2006 Dec 8;314(5805):1560-3.
- [10] Elinor Ostrom, Polycentric systems for coping with collective action and global environmental change, *Global Environmental Change*, Volume 20, Issue 4, 2010, Pages 550-557.
- [11] GOULDER, LAWRENCE H., and ANDREW R. SCHEIN. "CARBON TAXES VERSUS CAP AND TRADE: A CRITICAL REVIEW." *Climate Change Economics*, vol. 4, no. 3, 2013, pp. 1–28.
- [12] Sigmund, K. (2010). *The calculus of selfishness*. Princeton University Press. <https://psycnet.apa.org>
- [13] Luis R. Izquierdo, Segismundo S. Izquierdo, William H. Sandholm, An introduction to ABED: Agent-based simulation of evolutionary game dynamics, *Games and Economic Behavior*, Volume 118, 2019, Pages 434-462.
- [14] Matjaž Perc, Jillian J. Jordan, David G. Rand, Zhen Wang, Stefano Boccaletti, Attila Szolnoki, Statistical physics of human cooperation, *Physics Reports*, Volume 687, 2017, Pages 1-51.
- [15] Nowak, M., May, R. Evolutionary games and spatial chaos. *Nature* 359, 826–829 (1992).
- [16] Araujo, G. An evolutionary game theory for event-driven ecological population dynamics. *Theory Biosci.* 144, 95–105 (2025).

- [17] Nordhaus, William. "TIPPING POINTS IN THE CLIMATE CASINO." *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*, Yale University Press, 2013, pp. 50–66.
- [18] Sipos, B., Massingham, T., Jordan, G.E. et al. PhyloSim - Monte Carlo simulation of sequence evolution in the R statistical computing environment. *BMC Bioinformatics* 12, 104 (2011). Klaus Gugler, Adhurim Haxhimusa, Mario Liebensteiner.
- [19] Effectiveness of climate policies: Carbon pricing vs. subsidizing renewables, *Journal of Environmental Economics and Management*, Volume 106, 2021, 102405.
- [20] Chao Feng, Jian-Bai Huang, Miao Wang, Yi Song, Energy efficiency in China's iron and steel industry: Evidence and policy implications, *Journal of Cleaner Production*, Volume 177, 2018, Pages 837-845.