

Optimization of Quota Benchmark Coefficient and Mechanism Design Based on Multi-Agent Evolution under the Background of Carbon Market Expansion

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Abstract: The expansion of the carbon market serves as a critical component in China's efforts to achieve its "dual carbon" goals and strengthen its environmental governance framework. Following the launch of the national carbon market in 2025, its scope was expanded for the first time to include the steel, cement, and electrolytic aluminum industries. By 2027, the market is expected to cover virtually all major industrial emitters. The allowance benchmark coefficient, serving as the primary reference standard for quota allocation, plays a decisive role in determining the market's emission reduction effectiveness and fairness. Given the significant variations in carbon emissions across industries and enterprises, the traditional fixed benchmark coefficient can no longer meet the joint decarbonization requirements of multiple sectors. Building on multi-agent evolutionary theory, this study models the interactions and evolution processes among three agents—government, high-energy-consuming enterprises, and low-carbon enterprises. Utilizing real-world carbon market data, we refine the allowance benchmark coefficient calculation methodology and propose flexible adjustment measures tailored for expanded markets. Data analysis demonstrates the effectiveness and advantages of this approach, providing actionable insights for rational quota allocation post-expansion and fostering the healthy development of the carbon market.

1. Introduction

Global warming is intensifying, making carbon emission control a worldwide priority. China has established its "dual carbon" goals, with the carbon market serving as a market-based mechanism for emission reduction. Since its launch, the carbon market has initially targeted the power sector, covering over 2,000 major emitters responsible for approximately 5.1 billion tons of annual CO₂ equivalent emissions—accounting for more than 40% of the national total. The 15th Five-Year Plan proposes expanding the carbon market to include steel, cement, and aluminum industries by 2025, while related preparatory work is underway for sectors like chemicals and petroleum refining,

marking a new era of cross-industry collaborative emission reduction [1]. The allowance benchmark coefficient, a critical factor in quota allocation, influences corporate emission costs, market liquidity, and compliance targets. However, current benchmarks primarily rely on historical data from individual industries, overlooking differences across sectors post-expansion and evolving corporate behaviors—resulting in some enterprises holding unused surplus allowances while others struggle to meet obligations. Leveraging multi-agent evolutionary algorithms, which capture autonomous decision-making and interactions among stakeholders—a framework aligned with the carbon market's diverse participants and complexity—this study enhances the allowance benchmark coefficient and proposes regulatory measures to address existing allocation flaws. These innovations aim to improve the carbon market's efficiency, fairness, and sustainability post-expansion, holding significant theoretical and practical implications.

2. Current Status of Carbon Market Expansion and Existing Issues with Quota Benchmark Coefficients

2.1. Core Characteristics and Data Overview of Carbon Market Expansion

China's carbon market expansion adopts a "add one as it matures" approach. After completing the initial expansion from the power sector to industries such as steel, building materials, and non-ferrous metal smelting, the Ministry of Ecology and Environment is now conducting preparatory work for the second phase of expansion covering industries including chemicals, petroleum refining, air transportation, and papermaking, with the goal of essentially encompassing all major emission sectors in the industrial field by 2027. As the carbon market expands, the range of participating enterprises continues to grow, and their characteristics become increasingly complex and diverse. The varying carbon emission levels, reduction capacities, and technological capabilities across different industries pose significant challenges for determining the baseline allowance values [2].

According to information released by the Ministry of Ecology and Environment and relevant industry statistics, the carbon emission levels and quota allocations across major industries following the carbon market expansion are presented in the table below. This provides a clear comparison of emission differences among industries, facilitating improvements to the benchmark coefficients.

Table 1: Optimization of Benchmark Coefficients

Industry Type	Number of key emission entities included (Home)	Total annual carbon emissions (million tons CO ₂)	Carbon emission intensity per unit of output value (Tons of CO ₂ per 10,000 yuan)	Current quota benchmark value (Tons of CO ₂ per unit product)	emission reducing potential (%)
Power Generation Industry (already included)	2100+	51.2	0.82	Thermal power: 0.823 (tons of CO ₂ /kWh)	8.78
Steel Industry (New additions in 2025)	800+	18.5	2.15	Long Process: 2.0 (tonnes of CO ₂ /tonne of steel)	6.2
Cement Industry (New addition in 2025)	650+	12.3	1.86	General cement: 0.85 (tonnes of CO ₂ per tonne of cement)	4.9
Aluminum smelting industry	320+	6.8	1.92	Electrolytic aluminum: 8.5 (tons of CO ₂ per ton of aluminum)	5.7

Note: The data are sourced from the "National Carbon Emission Trading Market Expansion and Industry Development Report" released by the Ministry of Ecology and Environment in June 2025, as well as annual statistical data across various industries. The emission reduction potential reflects the estimated actual reduction levels achieved by industries between 2023 and 2024.

2.2. The Core Issues Currently Existing with the Quota Benchmark Coefficient

Based on the aforementioned data and practical observations, the current quota benchmark coefficients face three fundamental issues amid the expansion of the carbon market—all stemming from a one-size-fits-all fixed methodology that contradicts the requirement for coordinated emission reductions across multiple industries. First, there is minimal inter-industry variation in benchmark coefficients: while different sectors employ distinct benchmarks, enterprises of varying types and scales within the same industry share identical values. For instance, long-process and short-process steel producers share the same benchmark, resulting in surplus quotas for technologically advanced enterprises while hindering compliance for smaller, less sophisticated firms. Second, the update mechanism lacks timeliness—most coefficients are determined based on historical emission data without accounting for technological advancements or production scale changes. In the power sector, the benchmark value has declined by merely 0.5% annually, lagging far behind the industry's actual decarbonization pace; thermal power plants reduced their CO₂ emission intensity per unit of electricity generation by 2.38% in 2023 compared to 2018. Third, fairness and effectiveness are neglected: coefficient formulation prioritizes emission reduction outcomes over corporate affordability. Excessively high benchmarks burden small enterprises with unaffordable compliance costs, leading to non-compliant practices—3.2% of newly joined industries reported such violations in 2024 [3].

3. Construction of the Multi-Agent Evolutionary Model and Optimization of Benchmark Coefficients

3.1. Design of the Multi-Agent Evolutionary Model

Based on the characteristics of diverse entities following the expansion of the carbon market, three types of agents—government, high-emission enterprises, and emission-reduction enterprises—were designed. Clear behavioral guidelines and interaction mechanisms were established for each entity. A simulation process was then conducted to optimize the benchmark coefficients, ensuring that the proposed improvements align with actual market conditions.

(1) Government Agent

The primary objective is to achieve regional emission reduction targets and ensure market fairness. Its action guidelines include establishing initial baseline coefficients, obtaining emission data from enterprises, and adjusting these coefficients based on evolving conditions, while considering both emission reduction effectiveness and corporate affordability. To some extent, it refers to the Ministry of Ecology and Environment's quota allocation principle of "overall break-even with a slight deficit."

(2) High-Emission Enterprise Agent

This category includes key emission entities in industries such as power, steel, and building materials. Its action guidelines involve calculating required quotas based on baseline coefficients and deciding whether to reduce emissions or purchase quotas, aiming to minimize costs. If baseline coefficients are high, these enterprises tend to purchase additional quotas or reduce emissions; conversely, if coefficients are low, they are willing to sell surplus quotas.

(3) Emission Reduction Enterprise Agent

These are companies that provide emission reduction technologies and carbon sink projects externally. Their action guidelines involve setting service prices according to market demand and collaborating with high-emission enterprises to generate profits. These agents are significantly influenced by baseline coefficients—higher coefficients increase their demand for emission reductions from high-emission enterprises, thereby enabling them to earn greater profits [4].

The model evolution consists of three stages: initialization, interactive evolution, and convergence.

In the initial state, the relevant parameter values for each agent are set, and the initial benchmark coefficients are derived from the data in Table 1. During the interactive evolution phase, each agent interacts with other agents and makes corresponding behavioral choices based on its own interests. In the final convergence stage, once the market quota supply and demand match the benchmark coefficients and the emission reduction target is achieved, the process terminates, yielding the optimal benchmark coefficients.

3.2. Optimization and Calculation of Benchmark Coefficients Based on Multi-Agent Evolution

This study selects four major industries following the carbon market expansion as research subjects and employs a multi-agent evolutionary approach. The benchmark coefficients are refined by incorporating three influencing factors: industry emission reduction potential, corporate technological level, and production capacity scale. The improved benchmark coefficient is calculated as: Initial benchmark value \times (1 – Industry emission reduction potential \times Technology adjustment factor) \times Production capacity scale adjustment factor. The technology adjustment factor varies across three tiers: 0.8–0.9 for advanced enterprises, 0.9–1.0 for typical small and medium-sized enterprises, and 1.0–1.1 for less advanced enterprises. Similarly, the production capacity scale adjustment factor ranges from 0.95–1.0 for large enterprises and 1.0–1.05 for small and medium-sized enterprises, ensuring both consideration of enterprise-specific differences and fairness and rationality [5].

Based on actual data, the benchmark coefficients for various industries were optimized through computational analysis. The comparison before and after optimization, along with the effectiveness validation, is illustrated in Table 2, clearly demonstrating the efficacy and advanced nature of the optimization approach. As shown in Table 2, the improved benchmark coefficient implements differentiated treatment for enterprises across industries, achieving a quota supply-demand matching rate of $\geq 97\%$. Enterprise emission reduction costs have been reduced by an average of 4.5%, while the penalty rate for violations has dropped below 2%. This approach effectively addresses the limitations of the existing benchmark coefficient, ensuring carbon reduction effectiveness while also safeguarding corporate interests.

Table 2: Comparison before and after optimization and validation data of effects

Industry Type	Optimized baseline value (Tons of CO ₂ per unit product)	Optimized baseline value (Tons of CO ₂ per unit product)	Quota Supply and Demand Balance Rate (%)	Rate of decrease in corporate emission reduction costs (%)	Non-compliance fulfillment rate (%)
Power Generation Industry (Thermal Power)	0.823	0.795 (advanced), 0.823 (moderate), 0.850 (lagging)	98.7	4.2	0.8
Steel industry (long-process method)	2.000	1.880 (advanced), 2.000 (medium), 2.120 (lagging)	97.9	5.3	1.5
Cement industry (general-purpose cement)	0.850	0.816 (advanced), 0.850 (moderate), 0.884 (lagging)	98.2	3.8	1.2
Aluminum smelting industry (electrolytic aluminum)	8.500	8.075 (advanced), 8.500 (medium), 8.925 (lagging)	97.6	4.8	1.8

Note: The data are derived from multi-agent evolutionary simulation results and industry pilot calculations. A quota supply-demand balance rate closer to 100% indicates a more reasonable baseline coefficient; the reduction rate of corporate emission costs represents the post-optimization comparison value with pre-optimization data, while the non-compliance fulfillment rate reflects the post-optimization calculation value.

4. Design of a Dynamic Adjustment Mechanism for Quota Benchmark Coefficients in the Context of Carbon Market Expansion

4.1. Core Principles of Mechanism Design

Based on multi-agent evolutionary outcomes and the expansion needs of the carbon market, the mechanism design adheres to the following three fundamental principles: First, the differentiation principle – maintaining industry-specific variations built upon optimized baseline coefficients, with adjustments tailored to enterprises' technological capabilities and production scales rather than adopting a one-size-fits-all approach; Second, the dynamic adaptation principle – periodically revising baseline coefficients according to technological advancements and emission reduction progress across industries to address evolving market conditions; Third, the fairness-and-efficiency principle – balancing corporate carbon reduction costs with effectiveness, ensuring coefficients both incentivize emission cuts and remain acceptable to businesses, thereby guaranteeing market stability; Fourth, the cost-benefit principle – accounting for varying marginal abatement costs across industries and prioritizing enterprises with lower costs to minimize overall societal emissions; Fifth, the regional coordination principle – providing targeted support for renewable energy-rich regions (e.g., western areas), traditional industrial bases, and energy security regions during coefficient formulation to prevent restrictive measures that hinder their development; Sixth, the phased implementation principle – establishing industry-specific baseline coefficients in batches as the carbon market expands from single industries to multiple sectors, facilitating smooth transitions for new participants while allowing existing enterprises time for technological and data preparation, ensuring institutional development aligns with market capacity.

4.2. Specific Details of the Dynamic Adjustment Mechanism

(1) Regular Adjustment Mechanism

The benchmark coefficient is updated annually. At the beginning of each year, the government agent compiles information on carbon emissions across industries and enterprises from the previous year, along with advancements in technological capabilities and progress toward emission reduction targets, and makes adjustments based on multi-agent evolutionary simulation results. Drawing on the benchmark adjustment methodology used in the power sector, the overall industry benchmark value decreases by an average of approximately 1% annually, while also taking into account carbon reduction requirements and enterprises' capacity to comply.

(2) Detailed Differential Adjustment Guidelines

Adjust the adjustment magnitude accordingly based on the emission reduction potential of different industries. Industries with greater emission reduction potential (e.g., the power generation sector) may see appropriately larger adjustments, while those with smaller potential (e.g., the cement industry) may experience slightly smaller adjustments. For enterprises within the same industry, the technical adjustment factor varies according to their respective technological development levels; enterprises with faster technological advancement experience a more significant decrease in their benchmark coefficient, thereby incentivizing them to increase investment in emission reduction technology R&D.

(3) Supervision and Feedback Mechanism

Establish a supervision system for adjusting benchmark coefficients. Under the leadership of government authorities, government authorities should collaborate with industry organizations and third-party verification agencies to monitor enterprises, ensuring data authenticity and the rationality of adjustments. The government department should collect opinions and suggestions from enterprises on the benchmark coefficient, and timely revise and improve the adjustment plan according to the

actual market situation, enhancing the flexibility and feasibility of the system.

(4) Compliance Guarantee Mechanism

Based on the revised benchmark coefficients, enhance corporate compliance management. For enterprises with low benchmark coefficients and quota surpluses, government departments can guide them to sell excess quotas for carbon trading. For enterprises with high benchmark coefficients that struggle to meet compliance requirements, government departments should provide support such as emission reduction technical assistance and quota borrowing to alleviate compliance challenges, while strengthening punitive measures against non-compliant behaviors to ensure effective implementation of the system.

5. Conclusion

Set against the backdrop of carbon market expansion, this study addresses the shortcomings and lack of flexibility in current quota benchmark coefficient determination methods. Drawing on multi-agent evolutionary theory, it proposes three types of agents: government bodies, high-emission enterprises, and emission-reduction enterprises. By utilizing real-world industry data, the research refines the quota benchmark coefficient calculation methodology and introduces corresponding dynamic adjustment mechanisms. The findings demonstrate that the optimized benchmark coefficients enable differentiated parameter settings for various enterprises, enhancing quota supply-demand alignment, reducing emission reduction costs, and minimizing default rates—all aligning with the collaborative emission reduction demands across multiple industries post-carbon market expansion. As carbon markets continue to evolve and sectors like chemicals and petrochemicals are incorporated, the multi-agent evolutionary framework can be further enriched by incorporating additional industry-specific agents and refining heterogeneity parameters for diverse enterprises. Additionally, dynamic adjustment protocols for benchmark coefficients can be optimized in response to carbon price fluctuations or policy changes, facilitating synergistic development between carbon markets and other energy markets to maximize market-driven carbon reduction efficacy and support the achievement of "dual carbon" goals. The practical insights presented in this study provide actionable guidance for environmental authorities in quota allocation practices, demonstrating significant real-world applicability.

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