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Is the Emission Reduction Incentive of the National Carbon Emission Trading Market Effective? —An Analysis Based on Transaction Data

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Abstract: The national carbon emission trading market has been operating for more than four years since its official launch in July 2021, serving as a core policy instrument for China to advance its ambitious carbon peaking and carbon neutrality goals. As the world's largest carbon market by covered emissions, its operational efficiency and policy impact are of significant academic and practical interest. Using comprehensive market transaction data spanning from July 2021 to December 2024, this paper conducts an in-depth assessment of the emission reduction incentive effects of the national carbon market. The evaluation is structured across four critical dimensions: price signaling mechanisms, compliance requirements, overall cost savings, and market liquidity. The empirical results indicate that the national carbon market has achieved remarkable effectiveness in enforcing compliance requirements and generating substantial cost savings for participating entities. Notably, carbon prices have exhibited a sustained upward trend, successfully surpassing the 100-yuan-per-ton threshold, which strengthens the financial incentive for emission reductions. Furthermore, the compliance rate has been consistently maintained above 99.5%, and cumulative emission reduction costs have been significantly reduced by an estimated 40.5 to 48.1 billion yuan. Nevertheless, the analysis reveals that critical deficiencies persist in overall market liquidity and long-term carbon price stability. Addressing these challenges requires further institutional refinement, including the introduction of diverse trading products and the optimization of allowance allocation methods, to ensure the sustainable development of the carbon trading mechanism.

Keywords: carbon market; emission reduction; carbon allowances; transaction data; market effectiveness

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1. Introduction

Climate change is widely recognized as one of the most significant challenges confronting humanity. Among the various policy tools designed to address this issue, carbon emission trading has emerged as a prominent market-based mechanism. This approach facilitates cost-effective emission reductions while ensuring the achievement of environmental objectives. On July 16, 2021, China initiated its national carbon emission trading market, signifying a pivotal shift from regional pilot programs to a unified national framework. In January 2024, a comprehensive administrative framework was introduced to standardize the governance of the carbon market, marking a significant step forward in the legal and regulatory oversight of this system [1]. By the conclusion of 2024, the national carbon market had successfully completed three compliance cycles, demonstrating its operational maturity and potential for broader application.

In this context, a critical question arises: has the national carbon market effectively motivated enterprises to reduce their emissions? This issue is of paramount importance for policymakers and researchers, as it directly influences the optimization of the carbon

market's design and its capacity to support China's environmental objectives in a cost-efficient manner. The effectiveness of such market-based mechanisms is pivotal for achieving the nation's "dual carbon" goals, which aim to balance economic development with environmental sustainability. This paper leverages publicly available transaction data spanning from July 2021 to December 2024 to conduct a comprehensive evaluation of the incentive effects of the national carbon market. The analysis is structured across four key dimensions, providing a nuanced understanding of its performance. Based on these findings, the study offers targeted policy recommendations to enhance the market's effectiveness and ensure its alignment with broader environmental and economic goals [1, 2].

2. Theoretical Basis and Transmission Mechanism of Emission Reduction Incentives

2.1. Economic Foundations of Carbon Market Incentives

Carbon emission trading is fundamentally rooted in the Coase Theorem and the theory of property rights, which together provide a robust theoretical framework for understanding its economic rationale. According to the Coase Theorem, when property rights are clearly defined and transaction costs are negligible, the initial allocation of rights does not influence the efficiency of resource allocation. This principle underpins the design of carbon markets, where emission rights are treated as tradable assets. By transforming emission allowances into scarce commodities, the carbon market introduces a mechanism that generates price signals through quantity-based caps. These caps create artificial scarcity, compelling firms to internalize the cost of emissions into their operational strategies. The market thus incentivizes firms to minimize their emissions in a cost-effective manner, aligning private incentives with societal goals of reducing aggregate abatement costs. This approach ensures that emissions are reduced where it is most economically efficient to do so, thereby optimizing resource allocation across the economy [3].

The transmission mechanism of carbon market incentives operates through a structured process [2, 4]. Initially, the government establishes an emissions cap and allocates allowances to regulated entities. The scarcity of allowances leads to the formation of carbon prices, which firms incorporate into their cost-benefit analyses. Firms with low marginal abatement costs (MAC) find it advantageous to reduce emissions and sell surplus allowances, generating additional revenue. Conversely, firms with high MAC opt to purchase allowances to meet compliance requirements. This dynamic ensures that emissions reductions occur at the lowest possible societal cost. Furthermore, when carbon prices rise above a firm's MAC, it becomes economically viable for the firm to invest in advanced low-carbon technologies and equipment. This not only enhances the firm's competitiveness but also contributes to long-term emission reductions. The effectiveness of this mechanism is heavily influenced by the level and stability of carbon prices, as these factors directly impact the strength of the incentives for firms to adopt sustainable practices and technologies. A stable and sufficiently high carbon price is essential to drive meaningful investments in emissions abatement and to foster innovation in low-carbon solutions.

2.2. Evaluation Dimensions of Incentive Effectiveness

This study adopts four evaluative dimensions to comprehensively assess the effectiveness of incentives within carbon markets. These dimensions are designed to capture critical aspects of market performance and regulatory mechanisms, ensuring a holistic understanding of their impact. By focusing on these dimensions, the study aims to provide insights into whether the carbon market achieves its intended goals, such as promoting cost-efficient emissions reductions and fostering sustainable economic practices [5]. Each dimension addresses a specific facet of market functionality, ranging from price stability to operational efficiency, thereby offering a structured framework for evaluation.

1. Price signal effectiveness refers to the ability of carbon pricing mechanisms to maintain levels that are both sufficiently high and stable. This ensures that firms can cover their marginal abatement costs, thereby incentivizing them to adopt cleaner technologies and practices. Stability in carbon prices is crucial for long-term planning and investment in emissions reduction strategies, as unpredictable fluctuations may deter firms from committing to sustainable initiatives. By examining this dimension, the study evaluates whether the carbon market provides a reliable economic signal to drive environmentally responsible behavior.
2. Compliance constraint effectiveness examines whether the mandatory allowance-surrender system imposes binding requirements on enterprises covered by the carbon market. This dimension assesses the extent to which firms are compelled to adhere to emissions limits, ensuring accountability and alignment with regulatory objectives. The effectiveness of such constraints is pivotal in maintaining the integrity of the carbon market, as it prevents non-compliance and promotes equitable participation. By analyzing this aspect, the study seeks to determine whether the system effectively enforces emissions reductions without imposing undue burdens on enterprises.
3. Cost-saving effect evaluates whether the carbon market delivers lower abatement costs compared to traditional command-and-control approaches. This dimension highlights the economic efficiency of market-based mechanisms, which aim to minimize the financial burden on firms while achieving environmental goals. By enabling flexible trading and resource allocation, carbon markets can reduce the overall cost of compliance, making them a preferred alternative to rigid regulatory frameworks. The study explores this dimension to understand the comparative advantages of carbon markets in fostering cost-effective emissions reductions.
4. Market liquidity assesses the extent to which trading activity within the carbon market supports efficient price discovery and resource allocation. High liquidity ensures that participants can buy and sell allowances without significant price distortions, thereby enhancing market stability and functionality. This dimension is critical for evaluating the operational health of the carbon market, as robust trading activity reflects active engagement and confidence among stakeholders. By focusing on market liquidity, the study aims to identify potential barriers to efficient trading and propose solutions to enhance market performance.

3. Descriptive Analysis of the National Carbon Market Operation

3.1. Core Market Indicators

The national carbon market officially began operations on July 16, 2021, marking a significant milestone in China's efforts to address climate change and promote sustainable development [2, 6]. Initially, the market focused exclusively on the power sector, encompassing approximately 2,162 major emitting units. By the second compliance cycle, the scope of the market expanded to include 2,257 enterprises, collectively accounting for nearly 5 billion tons of carbon dioxide emissions annually. This expansion reflects the growing emphasis on comprehensive coverage and the inclusion of more industries to enhance the effectiveness of emissions trading as a policy tool. As of December 31, 2024, the cumulative trading volume of allowances reached an impressive 630 million tons, with a total turnover of 43.033 billion yuan. These figures underscore the robust activity within the market and its potential to drive significant reductions in greenhouse gas emissions. The steady increase in trading volume and turnover highlights the market's role as a critical mechanism for incentivizing emissions reductions and fostering innovation in low-carbon technologies.

Annual trading data from the national carbon market reveal a consistent pattern of stable transaction volumes coupled with rising allowance prices, indicating a maturing market dynamic. In 2024, the market operated for 242 trading days, achieving an annual allowance trading volume of 189 million tons and a record-breaking total turnover of

18.113 billion yuan. This represents the highest annual turnover since the market's inception, showcasing its growing economic significance. Block trades accounted for 37.027 million tons, generating 3.631 billion yuan, while bulk trades dominated with 151 million tons, contributing 14.482 billion yuan to the total turnover. Bulk trades represented 80.4% of the annual trading volume, highlighting their central role in market operations. Despite a year-on-year decline of 11.0% in trading volume compared to 2023, the market experienced a substantial 25.3% increase in turnover, driven primarily by strong price gains. This trend suggests that market participants are increasingly valuing allowances, reflecting heightened awareness of carbon pricing as a tool for achieving compliance and driving emissions reductions. The data also indicate a shift towards more strategic trading behaviors, as enterprises adapt to evolving market conditions and regulatory frameworks to optimize their carbon management strategies (As shown in Table 1).

Table 1. Core Operational Indicators of the National Carbon Market (2021--2024)

Year	Annual Trading Volume (100 million tons)	Annual Turnover (100 million yuan)	Average Transaction Price (yuan/ton)	Compliance Rate
2021	1.79	76.61	42.79	99.5%
2022	0.51	28.14	45.55	99.9%
2023	2.12	144.44	68.15	99.9%
2024	1.89	181.14	95.83	≈100%

Source: Shanghai Environment and Energy Exchange, Ministry of Ecology and Environment

3.2. Carbon Price Dynamics

In 2024, CEA closing prices exhibited significant fluctuations, ranging from 69 yuan to 106 yuan per ton, with notable upward momentum observed during the second quarter [7]. The psychological 100-yuan threshold was surpassed on April 24, when the closing price reached 104.33 yuan per ton. This marked a critical milestone in the market's development, reflecting heightened trading activity and investor confidence. However, the market experienced a partial correction in the subsequent months of May through August, during which prices moderated to approximately 90 yuan per ton. This adjustment phase likely stemmed from profit-taking behaviors and recalibrations in market expectations. By the fourth quarter, prices demonstrated renewed stability, fluctuating within the range of 97 to 106 yuan per ton. On November 13, the market achieved an all-time high of 108.5 yuan per ton, underscoring the robust demand dynamics and the evolving maturity of the carbon trading mechanism. The year concluded with a closing price of 97.49 yuan per ton, representing a substantial increase of 103.1% compared to the initial launch price in 2021 and a 22.75% rise from the end of 2023. These trends highlight the growing importance of carbon pricing as a tool for market-based environmental regulation and its potential to drive sustainable economic transitions.

Annual average prices for carbon allowances demonstrated a pronounced upward trajectory over the observed period, reflecting the market's progressive maturation and enhanced price discovery mechanisms. Starting at an average of 42.79 yuan per ton in 2021, the annual average price more than doubled to reach 95.83 yuan per ton by 2024. This sustained growth underscores the increasing confidence of market participants, bolstered by strengthened policy frameworks and improved regulatory oversight. The upward trend also indicates a more efficient alignment between supply and demand dynamics, as well as the gradual integration of carbon pricing into broader economic and industrial strategies. The consistent rise in average prices suggests that the market is transitioning from its nascent stages toward a more stable and predictable pricing

environment. This evolution is likely supported by enhanced transparency, better access to market data, and the growing participation of diverse stakeholders. Furthermore, the observed price trends may reflect the impact of external factors such as technological advancements in emissions reduction and the tightening of emissions caps, which collectively contribute to the market's overall robustness. These developments highlight the critical role of carbon pricing in incentivizing emissions reductions and fostering a low-carbon economy.

3.3. Temporal Distribution of Trading Activity

Trading activity in 2024 demonstrated a pronounced pattern heavily influenced by compliance requirements, with a significant concentration of trading volumes occurring in the fourth quarter. The quarterly distribution of trading volumes was markedly uneven, with Q1, Q2, and Q3 contributing 5%, 7%, and 9% of the annual totals, respectively, while Q4 accounted for a striking 79%. Within this period, December alone saw trading volumes peak at 75.3655 million tons, underscoring the intense focus on meeting end-of-year compliance obligations. The October to December period collectively contributed 76.53% of the total annual trading volume, further highlighting the dominance of short-term compliance strategies over more proactive and strategic carbon asset management approaches. This behavior suggests that enterprises are primarily reactive, prioritizing immediate regulatory requirements rather than adopting forward-looking practices that could optimize long-term carbon asset utilization and market engagement.

3.4. Compliance Performance

The national carbon market has achieved remarkable success in ensuring compliance among participating enterprises, with compliance rates reaching 99.5% in the first cycle, 99.9% in the second, and nearly 100% in the third. These figures underscore the effectiveness of the mandatory compliance framework, which has successfully encouraged enterprises to integrate emission costs into their operational strategies. This high level of adherence reflects the robustness of the market's design and its ability to incentivize responsible environmental practices. By fostering a culture of accountability, the system has minimized non-compliance and promoted sustainable development. The consistent improvement in compliance rates also highlights the growing maturity of the market and its alignment with broader environmental and economic objectives.

3.5. CCER Market Development

In 2024, the national voluntary greenhouse gas emission reduction market, known as the CCER market, was officially launched in Beijing. This marked a significant milestone in China's efforts to address climate change and promote sustainable development. The initial phase of the market saw the registration of over 40 new projects, which were developed under the first four approved methodologies. These methodologies provided a structured framework for quantifying and verifying emission reductions, ensuring the credibility and transparency of the system. Despite the introduction of new projects, trading activity remained heavily concentrated on pre-2017 legacy CCERs, which continued to dominate the market. The annual trading volume of these legacy credits exceeded 19.59 million tons, representing a 29% increase compared to the previous year. However, the shrinking supply of legacy credits led to a sharp rise in CCER prices, which converged to approximately 100 yuan per ton by the fourth quarter. This price level was nearly equivalent to the prices observed in the national carbon allowance market, highlighting the growing importance of CCERs as a flexible compliance mechanism. The expansion of the CCER system not only enhances the overall functionality of the national carbon market but also provides regulated entities with additional options to meet their emission reduction obligations in a cost-effective manner.

4. Multi-Dimensional Assessment of Emission Reduction Incentive Effectiveness

4.1. Price Signal Incentive: Sufficiency of Carbon Price Levels

Effective abatement incentives require carbon prices to adequately cover firms' marginal abatement costs, which represent the expense incurred for reducing an additional unit of emissions. The China Carbon Emission Trading Market Comprehensive Assessment Report 2025 highlights that the weighted average marginal abatement cost (MAC) for China's power sector ranges between 120 and 131 yuan per ton of CO2. This benchmark underscores the gap between current carbon pricing and the levels necessary to drive substantial decarbonization. While the 2024 average carbon price of 95.83 yuan per ton marks a significant improvement compared to earlier years, it still falls short of the threshold required to incentivize widespread adoption of advanced abatement technologies. This discrepancy indicates that while progress has been made, the current pricing framework may not yet be robust enough to catalyze transformative changes across the sector. Addressing this gap is critical for aligning economic incentives with long-term environmental objectives, particularly as industries face mounting pressure to transition toward low-carbon operations. Policymakers and market regulators must consider mechanisms to elevate carbon prices to levels that reflect the true cost of emissions reduction, thereby fostering a more effective and sustainable pathway to achieving national and global climate targets.

Price incentives have begun to demonstrate their potential in driving the adoption of medium- to low-cost abatement technologies. For instance, at a carbon price of 60 yuan per ton, technologies such as biomass co-firing become economically viable, enabling low-carbon retrofits for existing coal-fired power units. The price rally observed during 2023 and 2024 has further strengthened the economic case for these technologies, signaling a positive trend in the market's ability to support incremental emissions reductions. However, the current price levels remain insufficient to stimulate investment in high-cost, deep decarbonization solutions such as carbon capture, utilization, and storage (CCUS). These advanced technologies require significantly higher carbon prices to offset their substantial upfront costs and operational complexities. Additionally, pronounced price volatility within the carbon market poses a challenge to long-term investment certainty. Such fluctuations undermine the stabilizing role of price signals, which are essential for fostering confidence among investors and stakeholders. To address these issues, it is imperative to implement measures that enhance price stability and gradually elevate carbon prices to levels that can support both medium-term and long-term decarbonization strategies. A more predictable and robust pricing mechanism would not only incentivize technological innovation but also ensure alignment with broader climate policy objectives.

4.2. Compliance Constraint Incentive: Binding Enforcement

High and rising compliance rates demonstrate the effectiveness of the mandatory enforcement mechanism in regulating emissions. Enterprises are increasingly aware of the financial implications associated with exceeding emission limits, which has led to a significant shift in corporate behavior. The system ensures that organizations are held accountable for their environmental impact, fostering a culture of responsibility and adherence to established standards. By imposing tangible financial consequences, the mechanism incentivizes businesses to adopt more sustainable practices and integrate carbon management into their operational strategies [8, 9]. This approach not only mitigates environmental risks but also promotes long-term economic stability by aligning corporate objectives with broader ecological goals.

Survey data from the 2025 Comprehensive Assessment Report highlights a transformative shift in corporate attitudes toward carbon management. A notable 72% of key emitters have established specialized departments dedicated to managing carbon assets, reflecting a proactive approach to environmental governance. Furthermore, 87% of surveyed enterprises acknowledge the carbon market's significant influence on investment decisions, underscoring its role as a critical factor in strategic planning. The increasing allocation of resources to carbon management indicates a trend toward

institutionalization and professionalization, where environmental considerations are integrated into core business operations. This evolution extends beyond mere regulatory compliance, fostering innovation and reshaping internal governance structures to prioritize sustainability. By embedding carbon management into decision-making processes, enterprises are better positioned to navigate the complexities of the carbon market while contributing to broader environmental objectives.

4.3. Cost-Saving Effect: Least-Cost Abatement

A defining theoretical advantage of cap-and-trade systems is their ability to achieve least-cost social abatement, which refers to the minimization of costs associated with reducing emissions while meeting environmental targets. This mechanism allows for the allocation of abatement responsibilities across entities in a manner that ensures the most cost-effective reductions are prioritized. Empirical evidence has demonstrated that this theoretical advantage is not merely conceptual but has been realized in practical policy applications. By enabling entities with lower abatement costs to take on a larger share of the reduction burden, cap-and-trade systems optimize resource allocation and reduce overall economic strain. Furthermore, this approach incentivizes continuous improvement in operational efficiency and technological innovation, as entities seek to lower their abatement costs further to maximize their competitive advantage within the market framework [10, 11].

From 2019 to 2024, the carbon emission intensity of covered generating units experienced a cumulative decline of 2.9%, equating to an average annual reduction of 0.6%. This trend reflects the effectiveness of market-based mechanisms in driving measurable environmental improvements. On a broader scale, national full-caliber power generation emission intensity decreased by 6.1% in 2024 compared to 2019, underscoring the systemic impact of the carbon market [12–14]. When evaluated against a hypothetical scenario without market intervention, the carbon market facilitated a reduction in cumulative power-sector emissions by an estimated 357 to 484 million tons. Additionally, from 2020 to 2024, the national carbon market achieved cumulative cost savings ranging from 40.5 to 48.1 billion yuan, highlighting its economic efficiency. These outcomes illustrate the dual benefits of environmental progress and economic optimization, reinforcing the value of market-based approaches in addressing climate challenges.

The carbon market has also played a pivotal role in stimulating green innovation, as evidenced by the significant increase in low-carbon patent filings. Between 2019 and 2024, the number of low-carbon patents surged from fewer than 1,000 to over 4,000, indicating a robust response to market signals. This growth reflects the dynamic interplay between carbon pricing and technological advancement, where higher carbon prices incentivize investment in innovative solutions [2]. Statistical analysis reveals a positive correlation: each 1-yuan increase in carbon price corresponds to an additional 1.03 low-carbon patents. This relationship underscores the dual impact of carbon pricing, influencing both immediate abatement behaviors and long-term strategic investments in sustainable technologies. By fostering an environment conducive to innovation, the carbon market not only addresses current emission reduction goals but also lays the foundation for future advancements in low-carbon development.

4.4. Market Liquidity: Structural Shortcomings

Market liquidity, despite advancements in pricing mechanisms, compliance strategies, and cost-saving measures, continues to represent a significant challenge. The annual turnover rate in 2024 was recorded at a mere 3.5%, which is substantially lower compared to more established systems such as the European Union Emissions Trading System (EU ETS). This low turnover rate highlights the structural inefficiencies that hinder the development of a robust and dynamic trading environment. Addressing these shortcomings is essential for fostering a more active and efficient market that can better support long-term sustainability goals and economic optimization.

The underlying causes of low market liquidity can be attributed to several structural factors that limit the effectiveness and dynamism of trading activities. These factors

collectively constrain the ability of market participants to engage in continuous and strategic trading, thereby reducing overall market vibrancy and efficiency [15–17].

1. One significant factor is compliance clustering, where trading activities are concentrated around regulatory deadlines rather than being distributed throughout the year. This episodic trading behavior reflects a lack of continuous portfolio optimization, which is essential for a more balanced and liquid market. Encouraging year-round trading through policy adjustments or incentives could help mitigate this issue.
2. Another contributing factor is the narrow sectoral coverage of the market. Prior to 2025, the inclusion of only the power sector resulted in a limited diversity of market participants. This homogeneity restricts the potential for two-way trading, as the absence of varied stakeholders reduces opportunities for dynamic market interactions. Expanding sectoral coverage to include industries beyond the power sector could significantly enhance market depth and liquidity.
3. The shallow product menu also plays a critical role in limiting market liquidity. Currently, the market offers only spot allowance trading, with no availability of carbon futures, options, or other derivative instruments. This lack of financial products restricts participants' ability to manage risks effectively and hampers the process of price discovery. Introducing a broader range of trading instruments could provide participants with more tools to engage in strategic trading and risk management.
4. Lastly, the reliance on free allocation of allowances has a dampening effect on market liquidity. The limited use of paid auctioning reduces the scarcity of allowances, which in turn weakens the efficiency of price formation. Transitioning to a system with a higher proportion of auctioned allowances could create a more competitive environment, thereby enhancing both liquidity and price stability.

5. Deep-Seated Constraints on Incentive Effectiveness

1. Insufficient carbon price level and stability: Although the carbon price has doubled since its launch, it remains below the marginal abatement costs (MACs) of the power sector. This discrepancy limits its effectiveness in driving significant emissions reductions. Furthermore, price volatility, fluctuating between 69 and 106 yuan per ton, creates uncertainty for investors. This instability is primarily influenced by the tightness of quota allocations and uncertainties surrounding policy implementation. Such unpredictability undermines the confidence required for long-term investments in low-carbon technologies and infrastructure.
2. Chronic liquidity shortage: The market exhibits a low turnover rate of 3.5%, which reflects limited trading activity. Additionally, trading is heavily concentrated within specific timeframes, indicating a market primarily driven by compliance obligations rather than active participation in asset allocation. This lack of dynamic trading activity hampers the market's ability to facilitate effective price discovery and optimal resource allocation. Addressing these issues is critical to fostering a more robust and efficient carbon trading system.
3. Limited sectoral coverage: Until March 2025, the carbon market was restricted to the power sector, which significantly limited its diversity and the incentives for broader trading participation. However, the recent inclusion of additional sectors such as steel, cement, and aluminum is expected to expand the market's coverage to over 60% of national emissions. While this expansion represents a positive development, its full impact will only materialize gradually as these sectors adapt to the new regulatory framework and trading mechanisms.
4. Suboptimal allowance allocation: The current system heavily relies on free allocation of allowances, which reduces the scarcity necessary for efficient pricing. While baseline-based allocation methods reward more efficient units, they may not provide sufficient incentives for transformative technological advancements. A shift toward

auction-based allocation could enhance market efficiency by creating stronger price signals and encouraging deeper investments in innovative low-carbon technologies.

5. Underdeveloped carbon finance: The absence of advanced financial instruments, such as futures and options, limits the ability of market participants to hedge against price fluctuations. This lack of hedging tools increases exposure to price uncertainty, which can deter firms from committing to long-term investments in low-carbon technologies. Developing a more sophisticated carbon finance market is essential to providing the stability and predictability needed to support sustained emissions reductions and technological innovation.

6. Conclusions and Policy Recommendations

6.1. Main Conclusions

The national carbon market has generated meaningful emission-reduction incentives and measurable governance benefits, but its effects remain uneven across dimensions of market performance. Overall, the evidence indicates that the system has established a credible compliance framework and has begun to shape enterprise behavior in a lower-carbon direction. At the same time, important structural constraints continue to limit the depth, efficiency, and long-term signaling capacity of the market. These findings suggest that the market is functioning as an effective regulatory instrument in its current stage, yet it has not fully matured into a highly liquid and strongly price-discovering mechanism capable of delivering broader dynamic efficiency gains across all participants.

1. Compliance and cost-saving effectiveness: Near-perfect compliance rates and substantial cumulative cost savings indicate that the market has achieved strong regulatory effectiveness while also improving cost efficiency in emissions control. This demonstrates that covered entities are generally able to respond to the institutional requirements of the system and that market-based allocation and trading can reduce the aggregate cost of meeting emissions constraints. In practical terms, the market has already shown value not only as an administrative compliance tool but also as an instrument for lowering the economic burden of abatement relative to more rigid command-based approaches.
2. Innovation stimulus: Low-carbon patent activity has expanded significantly, and the positive relationship between carbon prices and innovation suggests that the market is beginning to influence longer-term technological adjustment. This is an important result because the ultimate effectiveness of carbon regulation depends not only on short-term compliance behavior but also on whether firms invest in cleaner production processes, energy efficiency improvements, and low-emission technologies. The observed innovation response indicates that even an evolving carbon market can contribute to dynamic transformation by encouraging firms to internalize future carbon constraints in their strategic planning and research decisions.
3. Price signal limitations: Although carbon prices have shown an upward trend, they remain below estimated marginal abatement costs, and price volatility is still pronounced. This implies that the current price signal is not yet sufficiently strong, stable, or predictable to guide optimal long-term investment decisions. A market can only fully perform its allocative and strategic functions when prices reflect scarcity with reasonable accuracy and continuity. At present, the gap between observed prices and abatement costs weakens the incentive for deeper emissions reductions and may delay capital reallocation toward cleaner technologies, especially for firms facing large upfront transition costs.
4. Liquidity as the key bottleneck: Low turnover and predominantly compliance-driven trading remain the central constraints on full market development. When trading activity is concentrated around compliance deadlines rather than distributed throughout the year, the market's capacity for price discovery, risk management, and efficient allowance reallocation is reduced. Limited liquidity can also amplify

volatility, discourage broader participation, and weaken confidence in the informational value of market prices. Therefore, while the market has established a functioning compliance architecture, its next stage of development depends critically on improving trading depth, participation breadth, and the regularity of transactions so that it can operate as both a regulatory mechanism and a mature market institution.

6.2. Policy Recommendations

1. Expand sectoral coverage steadily. A phased and criteria-based expansion strategy should be adopted to incorporate additional high-emission industries, including petrochemicals, chemicals, papermaking, and other major industrial sectors with significant mitigation potential. The principle of "mature one, include one" can help ensure that newly covered sectors enter the market only after emissions accounting rules, monitoring systems, verification capacity, and compliance procedures are sufficiently developed. This gradual approach can reduce implementation risks while improving regulatory consistency across sectors. By 2027, the carbon market should aim to cover the principal industrial emitting sectors on a broad basis, thereby increasing market participation, enhancing allowance trading diversity, and improving overall liquidity and allocative efficiency.

2. Introduce paid allowance allocation. The allowance allocation mechanism should gradually transition from a predominantly free allocation model toward a mixed free-and-paid system, with the share of auctioned allowances increasing in a predictable and transparent manner over time. Such a reform would strengthen the scarcity signal embedded in the market, improve the efficiency of carbon pricing, and create a more robust incentive structure for enterprises to invest in emissions reduction technologies and operational upgrading. In addition, revenue generated through paid allocation can be directed toward low-carbon transition support, technological innovation, industrial upgrading, and assistance for sectors facing higher adjustment costs. A balanced and well-calibrated allocation framework should be established by 2030 to better align market incentives with long-term decarbonization objectives.

3. Accelerate carbon financial innovation. The development of carbon finance instruments should be advanced in a prudent yet proactive manner. Carbon futures, options, and other derivatives can be introduced to improve market depth and provide regulated tools for price risk management. At the same time, products such as carbon pledge financing, repurchase arrangements, and other structured instruments can help activate the asset value of carbon allowances and related credits. A more complete financial product system would enhance price discovery, support hedging for compliance entities and investors, and contribute to more stable long-term expectations regarding abatement costs and investment returns. However, innovation should be accompanied by clear supervision, risk control standards, and disclosure requirements to prevent excessive speculation and maintain orderly market operation.

4. Enhance the CCER market. The CCER market should be strengthened by expanding methodology development, broadening the range of eligible project categories, and improving the quality assurance framework for project registration, monitoring, and verification. A larger and more credible supply of CCERs can reinforce the flexible compliance function of the carbon market, lower overall compliance costs, and provide additional incentives for emissions reduction and carbon sequestration activities beyond covered sectors. At the same time, strict standards for additionality, permanence, and transparency are essential to ensure environmental integrity and maintain confidence in offset use. Improving the linkage between the allowance market and the CCER mechanism would also help deepen market participation and increase overall market resilience.

5. Establish a carbon price stabilization mechanism. A formal price stabilization framework should be explored to reduce excessive carbon price volatility and preserve the effectiveness of the market signal. Possible instruments include a price corridor, which sets indicative upper and lower bounds for market expectations, and a market stability

reserve, which can adjust allowance supply in response to significant imbalances between supply and demand. Such mechanisms can help prevent persistently low prices that weaken incentives for emissions reduction, while also limiting excessively high prices that may impose abrupt compliance burdens on regulated entities. A well-designed stabilization mechanism would improve policy credibility, support investment planning, and enhance the long-term functioning of the carbon market by balancing environmental effectiveness with economic manageability.

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