

Carbon Trading Mechanism and Corporate Green Technology Innovation: A Theoretical Framework of Resource Allocation Efficiency

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Abstract

Against the backdrop of advancing "dual carbon" goals and improving the national carbon market, carbon trading has become a key external driver for corporate low-carbon transformation. Unlike traditional command-and-control environmental regulations, carbon trading transforms carbon emissions into measurable, tradable, and manageable operational costs through quota allocation, carbon price formation, and compliance obligations. These market-based mechanisms further influence enterprises' investment strategies, production plans, and R&D decisions. This paper analyzes the logical chain linking carbon trading mechanisms, resource allocation efficiency, and corporate green technological innovation. The study finds that carbon trading can boost enterprises' willingness to pursue green innovation through price signals and quota constraints. However, this effect does not occur automatically; it relies on resource allocation efficiency as a core channel. Only when enterprises redirect capital, R&D personnel, equipment, and management resources from energy-intensive, low-efficiency processes to energy-saving, low-carbon and green technologies can carbon constraints effectively drive substantive innovation. Accordingly, the paper proposes two key recommendations: further improving carbon price discovery mechanisms and quota allocation systems; and guiding enterprises to build carbon-cost-oriented resource allocation frameworks, to maximize the incentive effect of carbon trading policies on green technological innovation.

Keywords

Carbon Trading Market Mechanism; Green Technological Innovation; Efficiency of Resource Allocation; Carbon Price and Quota Constraint.

1. Introduction

Global climate governance has evolved beyond mere environmental concerns to encompass economic restructuring and the enhancement of corporate competitiveness. In 2020, China set ambitious targets: to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 [1]. This necessitates that energy-intensive enterprises shift their development focus from scale expansion to efficiency improvement and technological advancement. To realize these goals, China has progressively established a market-based environmental regulatory framework centered on carbon emission trading. The national carbon emission trading market commenced operations in 2021 [2], with its first compliance cycle covering 2,162 major emission entities in the power generation sector, accounting for approximately 4.5 billion tons of annual greenhouse gas emissions [3]. This demonstrates that carbon trading has transcended being merely a macro-level policy tool; it has now become integral to corporate operational practices and resource allocation processes.

From an enterprise perspective, the key impact of the carbon trading market mechanism lies in altering how companies assess the costs associated with their emission behaviors. Previously, some enterprises viewed carbon emissions as externalities and relied primarily on administrative mandates for reduction efforts; under the carbon trading system, emission allowances become scarce, and carbon prices reflect the costs of emission reduction through the trading market. When an enterprise's actual emissions exceed its allowance, it must purchase additional allowances or face compliance pressure; when it reduces emissions through technological upgrades, it may save costs or even gain allowance-based benefits. This mechanism provides new economic incentives for enterprises to pursue green technological innovation.

However, the impact of carbon trading on green innovation is not a simple linear relationship. Whether enterprises increase their R&D investment in green technologies depends on the stability of carbon prices, the strength of quota constraints, and the ability to promptly reallocate internal resources. If corporate funds are allocated to inefficient projects, R&D resources are dispersed, or management focuses solely on short-term compliance costs, carbon trading may merely impose cost pressures rather than fostering sustained innovation momentum. Therefore, this paper uses resource allocation efficiency as a mediating variable to analyze how carbon trading market mechanisms influence corporate green technological innovation, aiming to provide insights for business decision-making and the optimization of carbon market institutions.

2. Theoretical Basis

The core theoretical logic of the carbon trading system lies in converting environmental capacity into scarce emission rights and achieving the reallocation of emission reduction resources through market transactions. Montgomery was among the first to demonstrate that under cap-and-trade frameworks, tradable permits enable the redistribution of pollution control resources among different entities, thereby achieving predetermined emission reduction targets at lower costs [4]. This theory underscores that the significance of carbon trading extends beyond emission limitation; more importantly, it utilizes price signals to direct resources toward entities with lower emission reduction costs and higher efficiency. At the corporate level, the carbon market essentially functions as a resource reallocation mechanism under external constraints.

Theoretical explanations of how environmental regulations influence corporate innovation primarily revolve around two approaches: "compliance costs" and "innovation compensation." Traditional views hold that environmental regulations increase corporate costs, diverting resources from R&D and investment; the Porter Hypothesis suggests that well-designed environmental regulations can compel firms to improve their technologies and management processes, partially or even fully offsetting compliance costs [5]. Popp's analysis of U.S. patent data revealed that rising energy prices drive innovations in energy-saving technologies [6], demonstrating how price signals influence corporate technological choices. Acemoglu et al. further argue that environmental constraints enable policies to redirect technological progress, channeling R&D resources from "dirty technologies" toward "clean technologies" [7]. Thus, green technological innovation does not stem solely from corporate initiative; external pricing mechanisms, institutional frameworks, and policy signals collectively shape corporate innovation directions.

The prerequisite for carbon trading to foster green innovation is that enterprises can transform external constraints into internal resource reallocations. International studies on the EU carbon trading system have found that carbon trading enhances low-carbon innovation activities among regulated firms [8]; domestic research based on carbon trading pilots also demonstrates

that carbon trading promotes green innovation among listed companies in heavily polluting industries [9], that market-based environmental regulations drive technological innovation [10], and may even facilitate breakthrough innovations [11]. However, these effects do not occur uniformly across all enterprises. Cao Hongjian et al. emphasize that property rights definition, market transactions, and transaction costs collectively influence the resource allocation efficiency of carbon markets [12]. This indicates that the ultimate effectiveness of carbon trading in driving innovation hinges on whether enterprises can reallocate their internal resources in alignment with carbon costs and emission reduction targets.

3. The Mechanism of the Carbon Trading Market and Its Impact on Green Technology Innovation

3.1. Carbon Price Signal: Transforming Emission Behavior into Measurable Costs

The carbon price serves as a direct signal of how carbon trading impacts corporate innovation, transforming previously abstract environmental externalities into measurable operational costs for businesses. When making project investments and technology choices, companies typically compare the costs, benefits, and risks of different options. With a clear and stable carbon price, enterprises can incorporate future carbon costs into their investment evaluations, viewing investments in energy-efficient equipment, low-carbon processes, and green product development as means to reduce long-term expenses. In this context, green technological innovation transcends mere social responsibility fulfillment and becomes a vital strategy for companies to control costs and enhance competitiveness.

Conversely, if carbon prices remain persistently low or experience excessive volatility, enterprises' expectations regarding returns from green R&D become unstable. Some companies may prefer to purchase emission allowances in the short term to meet compliance requirements rather than invest in green technological upgrades that require longer implementation cycles and entail higher risks. This demonstrates that carbon prices must accurately reflect the scarcity of emission reductions to consistently influence enterprises' technological strategy choices. The clearer the price signals, the more likely enterprises are to integrate green innovation into their medium-and long-term strategies, rather than remaining at the level of passive compliance.

3.2. Quota Constraints: Altering Corporate Compliance Pressure and Technology Choices

Quota constraints determine the emission allowance available to enterprises and the compliance pressure they face. If quota allocations are too lenient, enterprises can meet their compliance requirements without implementing technological upgrades, resulting in insufficient incentives for green innovation; if quotas are tightened too rapidly, short-term costs may rise significantly, squeezing normal production and R&D investments. Therefore, the quota mechanism must strike a reasonable balance between emission reduction pressures and enterprises' capacity to bear them.

Under reasonable constraints, the quota shortfall will compel enterprises to reassess their energy mix, production processes, and equipment efficiency. For energy-intensive enterprises, quota restrictions increase the hidden costs of inefficient production capacities and high-emission processes; for companies with stronger technological foundations, these constraints may serve as an external driver to accelerate green R&D and technology commercialization. Particularly as carbon trading coverage expands and quotas gradually tighten, the earlier enterprises develop energy-saving and carbon-reduction technologies, the greater their likelihood of gaining a cost advantage in future competition.

3.3. Information Disclosure and External Resources: Amplifying Incentives for Green Innovation

Carbon trading also indirectly influences green innovation through information disclosure, external financing, and reputation mechanisms. Companies participating in the carbon market must conduct emission accounting, data reporting, and compliance management, which increases the attention of external investors, financial institutions, and government departments toward their low-carbon performance. Enterprises with well-regulated carbon management practices and strong green innovation capabilities are more likely to secure green credit, green bonds, or government project support, thereby providing resource backing for subsequent technological innovation.

Conversely, if enterprises persistently rely on high-emission models, they will not only incur costs associated with quota purchases and compliance obligations but may also face adverse financing conditions and diminished market recognition due to their weak low-carbon performance. Thus, carbon trading is not merely a cost-pressure mechanism; rather, it collectively influences corporate green technological innovation through pricing, quota allocation, information disclosure, and resource evaluation. Whether enterprises can effectively respond to these external signals hinges critically on their internal capabilities in resource allocation and management responsiveness.

3.4. Summary of the Action Path

Overall, carbon trading influences green technology innovation through three primary mechanisms: first, by increasing emission costs through carbon pricing, thereby enhancing the relative returns on green technology investments; second, by creating compliance pressures through quota constraints that drive enterprises to phase out energy-intensive and inefficient processes; third, by strengthening financing and reputation incentives for green innovation through information disclosure and external resource assessments. These mechanisms collectively reshape corporate cost-benefit structures, but their effective translation into actual innovative actions hinges on the intermediary role of efficient resource allocation.

4. Analysis of the Mediating Role of Resource Allocation Efficiency

4.1. Resource Allocation Efficiency is the Critical Link in Transforming External Constraints into Internal Innovation

The efficiency of resource allocation hinges on whether capital, labor, technology, and managerial resources are directed toward uses yielding higher marginal returns. Wurgler argues that financial markets reflect capital allocation efficiency through investment flows [13]; Hsieh and Klenow, from the perspective of resource misallocation, demonstrate that distorted factor allocation reduces productivity [14]. In the context of carbon trading, resource allocation efficiency not only indicates whether funds are invested in high-return projects but also determines whether enterprises can reallocate resources from high-carbon, inefficient processes toward energy conservation, carbon reduction, and green R&D initiatives.

Therefore, resource allocation efficiency can explain how carbon trading influences green technological innovation. While carbon trading provides external signals, the absence of integrated capital management, focused R&D efforts, and organizational synergy within companies may cause price and quota pressures to manifest solely as compliance costs; only when firms can reallocate capital, R&D, and management resources can carbon constraints be further translated into green technological innovation.

4.2. Capital Allocation Efficiency: Shifting from Expansionary Investment to Low-Carbon Investment

From a capital allocation perspective, carbon trading will alter the expected returns of different projects. Traditional energy-intensive equipment may still contribute production capacity in the short term; however, if carbon costs continue to rise in the future, their actual returns will decline. Although energy-saving technological upgrades, clean energy substitution, and low-carbon product development require substantial upfront investment, they can reduce compliance costs and enhance competitiveness over the long run. Therefore, enterprises need to incorporate carbon costs into their capital budgets and redirect investments from merely expanding production capacity toward equipment renewal, energy management, and green process improvements.

The higher the efficiency of capital allocation, the more easily carbon price signals can be translated into green investments. Conversely, if companies continue to allocate funds based on past capacity expansion logic, a situation may arise where there are carbon constraints but no corresponding innovation responses. For example, although companies recognize that future carbon costs will rise, their funds remain tied up in inefficient equipment, excess capacity, or short-term projects, making it difficult to sustain investment in green R&D and technological upgrades. In such cases, the policy effects of carbon trading are undermined by internal resource misallocation.

4.3. Efficiency of R&D Resource Allocation: Transitioning from Decentralized R&D to Addressing Key Emission Reduction Challenges

From the perspective of R&D resource allocation, green technological innovation is typically characterized by long cycles, high risks, and strong cross-departmental collaboration requirements. Simply increasing R&D spending does not necessarily lead to effective innovation; the key lies in whether R&D resources are concentrated on areas with emission reduction potential and commercial viability. For example, in industries such as steel, power, and chemicals, green innovation may encompass multiple aspects including low-carbon processes, energy efficiency optimization, carbon capture and utilization, and intelligent energy management. Enterprises must identify the most effective technological directions for reducing carbon costs based on their emission profiles and core business operations.

When R&D projects are overly fragmented or primarily aimed at securing policy recognition and patent counts, innovation tends to remain at a strategic level rather than genuinely enhancing companies' emission reduction capabilities. Conversely, by concentrating R&D resources on key emission sources, customers' low-carbon demands, and industry technology trends, companies are more likely to achieve substantive green technological innovations. This also explains why different enterprises exhibit markedly divergent innovation outputs when facing carbon trading policies.

4.4. Efficiency of Resource Allocation Management: Integrating Carbon Management into Business Decision-Making

Beyond capital and R&D resources, the allocation of management resources also significantly influences the innovation outcomes of carbon trading. Green technology innovation is not the sole responsibility of the R&D department; it involves multiple aspects such as financial budgeting, production upgrades, supply chain management, market positioning, and strategic planning. If carbon management remains confined to compliance departments, companies may focus solely on meeting their quota obligations during each compliance cycle, neglecting long-term technological advancement initiatives.

A more effective approach involves the collaborative participation of finance, production, R&D, and strategy departments in carbon management. The finance department calculates carbon

costs and investment returns; the production department identifies high-emission processes; the R&D department proposes technical solutions; and the strategy department evaluates green products and market opportunities. Through this cross-departmental resource integration, carbon trading can evolve from a mere compliance requirement into an integral part of corporate innovation and competitive strategy.

4.5. Logic of the Mediating Effect

This establishes a relatively comprehensive mediating mechanism: Carbon trading alters corporate cost-benefit structures through price and quota signals, prompting firms to reallocate capital, R&D, and management resources under this pressure. Enhanced resource allocation efficiency subsequently increases investment and output in green technological innovation. According to the mediating effect theory, resource allocation efficiency explains the indirect pathway through which carbon trading influences green innovation [15]. In subsequent empirical studies, stepwise regression and the Bootstrap method can be employed to test the significance of the indirect effects [16], while separately examining the mediating roles of capital allocation efficiency, R&D resource allocation efficiency, and management synergy efficiency.

5. Practical Issues and Optimization Recommendations

5.1. Real-world Issues

5.1.1. Weak Carbon Price Signals Lead to Insufficient Long-term Innovation Expectations among Enterprises

The current carbon market still suffers from insufficient trading activity and inadequate price signals. If carbon prices fail to accurately reflect the scarcity of emission reductions, companies will struggle to assess the long-term returns on green technology investments. Some firms may view carbon trading merely as a short-term compliance obligation-purchasing allowances or cutting current costs to meet regulations-rather than committing to long-term green R&D initiatives.

5.1.2. Insufficient Refinement in Quota Allocation May Weaken Innovation Incentives

Quota allocation directly impacts corporate emission reduction pressures. If the proportion of free allowances is excessively high or the quota framework is overly lenient, enterprises lack motivation for proactive technological upgrades; conversely, if quotas are tightened too rapidly, companies may allocate resources to short-term cost containment rather than long-term innovation. Given the significant variations across industries in technological foundations, emission reduction potential, and operational pressures, a uniform, broad-based quota arrangement struggles to balance emission reduction targets with innovation incentives.

5.1.3. Significant Disparities in Corporate Resource Allocation Capabilities, Coupled with Inadequate Innovation Responsiveness among Small and Medium-sized Enterprises

Different enterprises exhibit varying capacities for resource reallocation in carbon trading scenarios. Large corporations typically possess robust financing capabilities, solid R&D foundations, and effective management systems, enabling them to more readily transform carbon constraints into technological advancements; in contrast, small and medium-sized enterprises often face challenges in pursuing systematic green innovation due to insufficient funding, limited talent, and weak carbon accounting capabilities. Even when external policy signals are established, internal resource misallocation within companies can still undermine policy effectiveness.

5.1.4. Insufficient Synergy between Carbon Markets and Green Finance/Technology Policies

Green technology innovation requires long-term funding and policy support; relying solely on carbon trading is insufficient. Without effective coordination among carbon markets, green finance, fiscal subsidies, and technology projects, enterprises may hesitate to invest-even if they are willing to upgrade their technologies-due to high financing costs, lengthy project timelines, and uncertain risks. Consequently, the incentive effect of carbon trading policies must be amplified through the combined use of other policy instruments.

5.2. Optimization Suggestions

5.2.1. In Response to Weak Price Signals: Enhance Market Liquidity and Price Discovery Capabilities

To address the issue of insufficient carbon price signals, it is essential to further enhance the trading activity and price discovery capabilities of the carbon market. On one hand, under controllable risk conditions, the range of trading participants and methods can be gradually expanded to improve market liquidity; on the other hand, carbon emission data verification and information disclosure should be strengthened to alleviate corporate concerns regarding price signals. Only when carbon prices more accurately reflect the cost of emission reduction will enterprises incorporate future carbon costs into their investment decisions and view green technology innovation as a source of long-term returns.

5.2.2. Addressing Quota Allocation: Establishing a Dynamic Quota Mechanism by Industry and Phase

To address the issue of insufficient refinement in quota allocation, a differentiated approach should be adopted based on industries' technological foundations, emission reduction potential, and enterprise scale. For industries with mature technologies and significant emission reduction opportunities, quota constraints can be gradually tightened to encourage enterprises to accelerate equipment upgrades and process improvements; for industries facing substantial short-term transition pressures, a reasonable transition period should be established to avoid excessive quota tightening that could undermine legitimate R&D investments. Additionally, over-reliance on free quotas should be reduced, ensuring that quota constraints genuinely drive innovation rather than serving merely as a formal compliance requirement.

5.2.3. Addressing Insufficient Corporate Resource Allocation Capacity: Establishing an Internal Resource Allocation System Oriented Toward Carbon Costs

To address the issue of internal resource misallocation within enterprises, companies should establish a resource allocation system oriented toward carbon costs. First, incorporate carbon prices, quota deficits, and compliance costs into capital budgets, and set stricter investment thresholds for projects involving the expansion of energy-intensive equipment. Second, in R&D management, prioritize projects based on major emission sources and industry-specific emission reduction challenges, while reducing strategic innovations solely focused on patent quantity. Third, enterprises should establish a cross-departmental carbon management mechanism where finance, production, R&D, and strategy departments jointly participate in low-carbon investment decisions, integrating green innovation with core business upgrades.

5.2.4. Addressing Insufficient Policy Synergy: Strengthening the Linkage Between Carbon Markets, Green Finance, and Technology Policies

To address the issue of insufficient policy coordination, it is essential to strengthen the alignment between carbon markets and green finance, fiscal subsidies, and science and technology policies. Enterprises that invest heavily in green R&D, demonstrate significant emission reduction achievements, and maintain standardized carbon data disclosure should receive support in areas such as green credit, green bonds, and technology project applications,

thereby reducing uncertainties associated with long-term innovation. For small and medium-sized enterprises, public technology service platforms, carbon accounting training programs, and special funds for green technology upgrades can help enhance their carbon management and resource allocation capabilities. Only in this way can the external pressures of carbon trading be effectively translated into innovative actions that are both feasible and actionable for businesses.

6. Conclusion

The carbon trading market mechanism exerts a significant influence on corporate green technological innovation, though this impact does not occur automatically. Carbon prices and quota constraints alter enterprises' perceptions of emission costs and returns on green investments, providing external incentives for green technological innovation; however, what ultimately determines the policy's effectiveness is whether enterprises can enhance resource allocation efficiency by directing capital, R&D, and management resources toward developing low-carbon processes, energy-efficient equipment, and green products. Thus, resource allocation efficiency serves as the critical intermediary through which carbon trading influences green technological innovation.

The analysis in this paper indicates that improving the carbon trading market mechanism and enhancing enterprises' internal resource allocation capabilities should be advanced concurrently. Governments need to strengthen the carbon market's incentive role for green innovation through more effective price discovery, more scientific quota allocation, and better-coordinated green finance policies; enterprises, in turn, should transform carbon constraints into strategic management variables and enhance their green technology innovation capabilities through capital allocation and restructuring of R&D resources. Subsequent research could conduct empirical tests using panel data from listed companies to compare the differences in mediating effects across various industries, enterprise sizes, and ownership structures, thereby providing more robust empirical evidence for refining carbon market institutions and facilitating corporate low-carbon transformation.

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