

**Research Article****SMART CARBON MARKETS DESIGN IN CHINA: ENHANCING DATA TRANSPARENCY AND DRIVING DIGITAL INNOVATION UNDER THE DUAL CARBON GOALS*****Tijouit Asmaa**

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Abstract

China's national carbon market has become a key tool for the government to achieve the significant emission cuts needed for the 2060 carbon neutrality target. However, a review of its design and operation from 2010 to 2024 shows that the system still does not work as a strong, market-based climate policy. This paper argues that three interconnected risks mutually reinforce each other. First, informational risks stem from inconsistent and sometimes unreliable measurement, reporting, and verification (MRV) systems, which distort emissions data and create opportunities for strategic misreporting. Second, regulatory risks arise from fragmented rules, relatively low penalties, and weak enforcement, keeping the expected cost of non-compliance low. Third, market risks result from persistent allowance oversupply, which depresses prices and weakens the marginal abatement cost (MAC) signal that should guide low-carbon investment. The primary contribution of this study is to propose a dual-pillar mitigation framework for transforming China's national carbon market from a primarily administrative compliance tool into a more effective economic instrument. The first pillar involves leveraging technology to automate data collection and verification, including blockchain for securing transactions and allowance records, the Internet of Things (IoT) systems for continuous emissions monitoring and near real-time data, and artificial intelligence (AI) for anomaly detection and optimizing the Market stability reserve (MSR). The second pillar centers on governance reforms, including strengthening the market's legal foundation by replacing temporary administrative measures with binding national regulations, transitioning to full allowance auctioning, and instituting penalties that consistently outweigh the economic benefits of non-compliance.

Keywords: China's national carbon market, Smart carbon markets, Emissions trading system (ETS), Digital MRV, Carbon price signal.**INTRODUCTION**

China's national carbon emissions trading system (ETS) is now one of China's key tools for reaching its "dual carbon" targets peaking emissions before 2030 and achieving carbon neutrality by 2060. After growing out of regional pilot programs, the national market has put a basic compliance structure in place and introduced a carbon price signal meant to guide firms toward cutting emissions. But what we have seen in practice from 2010 to 2024 is that the system still does not work like a fully market-driven climate policy: the quality and credibility of emissions data vary, enforcement is uneven, and allowances are often not scarce enough to create a clear marginal abatement cost (MAC) signal [1]. In this paper, we argue that these weaknesses come from three problems that reinforce each other. First, there are informational risks: measurement, reporting, and verification (MRV) rules and practices are not always consistent, and verification capacity can be limited, which makes emissions data less reliable. Second, there are regulatory risks: rules are sometimes applied unevenly, penalties may not be strong enough to deter non-compliance, and enforcement gaps reduce the real cost of violating requirements. Third, there are market risks: when allowances remain in oversupply, prices stay weak, price discovery is limited, and firms have less incentive to invest in low-carbon upgrades [2]. The good news is that the timing is right to improve the system. China's fast digital transformation, together with recent efforts to strengthen ETS governance through higher-level legal authority, creates a practical opening to raise market integrity and efficiency.

Building on this opportunity, we propose a dual-pillar approach: using digital tools (such as blockchain, IoT (the Internet of Things) / CEMS (continuous emissions monitoring systems), and AI for anomaly detection and Market stability reserve (MSR) support) to strengthen data governance, while also pushing institutional reforms that clarify rules, improve coordination, and design penalties strong enough to make compliance the rational economic choice [3]. The remainder of the article is organized as follows. Section 2 reviews the literature on the performance, risks, and digital transformation of China's carbon market. Section 3 analyzes informational risks, focusing on MRV weaknesses, information asymmetry, and the distortion of the carbon price signal. Section 4 discusses technology-driven solutions for building a smart carbon market, including blockchain and IoT-based data foundations and AI-enabled oversight and stabilization mechanisms. Section 5 examines governance and regulatory enhancements needed to make digital upgrades effective, including legal formalization, enforcement strengthening, and policy mandates for digital integration. Section 6 concludes with key findings and policy recommendations.

LITERATURE REVIEW

Research dedicated to China's national carbon market has expanded dramatically over the past decade, initially spurred by the implementation of foundational regional pilot programs in major economic centers like Beijing, Shanghai, and Guangdong. Early academic scrutiny focused primarily on evaluating the efficacy of carbon trading as a mechanism for achieving measurable emissions reductions and influencing corporate environmental behavior. Findings generally affirm that the market has indeed contributed to curbing emissions

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within regulated sectors; however, scholars consistently note that the impact is heterogeneous, varying widely due to diverse regional industrial compositions and the rigor of local regulatory enforcement [4]. Furthermore, a major consensus points to the underdeveloped nature of the market's price stabilization mechanisms, resulting in persistently low liquidity and weak, ambiguous carbon price signals. These foundational studies collectively conclude that while China has successfully established the necessary policy framework, its current operational capacity requires significant structural reinforcement to drive the sustained, long-term low-carbon transformation required [5].

A second, more critical stream of literature pivots to investigate the fundamental data transparency and verification challenges that actively undermine market efficiency. Researchers repeatedly emphasize that emissions reporting systems across regulated industries are often deeply fragmented, plagued by inconsistencies in fundamental measurement methodologies, monitoring standards, and data disclosure practices [6]. This systemic disarray generates persistent information asymmetry between regulators, reporting enterprises, and the financial market, thereby limiting the precision of allowance allocation and the effectiveness of market oversight. Compounding this, studies by Zhou and Li and others highlight how inadequate third-party verification capacity and uneven regional governance inevitably lead to highly variable compliance reliability[7]. The core conclusion here is stark: without standardized, trustworthy data, the carbon price cannot accurately reflect genuine environmental costs, fatally weakening the incentive for firms to invest in green innovation. Consequently, improving data governance is universally identified as the essential prerequisite for strengthening the credibility and overall performance of the Chinese carbon market [8].

More recent scholarship marks a pivotal shift, moving beyond problem identification to explore technological innovation as a definitive solution to enhance market transparency and efficiency the very area where this paper contributes [9]. Academic discourse now centers on how cutting-edge technologies can radically upgrade market operations. For instance, scholars argue that blockchain can provide secure, tamper-proof records for carbon allowances, while AI and big data analytics are poised to forecast complex price trends and automatically detect anomalies in trading behavior. Similarly, the IoT is recognized as a critical enabler for achieving real-time emissions monitoring, drastically improving the accuracy of enterprise-level reporting [10]. While early pilot applications in provincial markets offer compelling evidence that digital tools can reduce verification costs and significantly increase trust in transactions, researchers concurrently issue a necessary caution: the integration of these technologies demands the urgent establishment of a standardized data architecture, coordinated national regulatory systems, and substantial upfront investment in digital infrastructure. The collective literature thus confirms the immense transformative potential of technological innovation to evolve China's carbon market into a smart, data-driven system, but critically emphasizes the need for a coherent national strategy to guide this complex transitionmate data collection in real-time, and provide sophisticated algorithms to detect irregular trading or non-compliance. The strategic integration of these digital solutions can transform the China National Carbon Market from a conventional, compliance-driven framework into a smart, data-

driven, and innovation-oriented market. This paper, therefore, is dedicated to examining how these technological advancements can decisively improve data governance and accelerate China's broader climate goals. By offering a comprehensive analysis of current risks and technological opportunities, this study provides practical, actionable pathways for building a transparent, credible, and modern carbon market capable of effectively guiding China's critical climate transition [11].

Data Transparency and Informational Risks in China National Carbon Market

The efficacy of China's carbon market is fundamentally dependent on the integrity and reliability of its emissions data. When these data inputs are compromised—through inconsistency, inaccuracy, or lack of standardization—the market is exposed to significant informational risks that directly violate principles of efficient resource allocation and market fairness [12]. These risks, which form the cornerstone of the system's operational instability, are analyzed across three interwoven domains: the systemic failures of the MRV process, the resulting information asymmetry, and the subsequent distortion of the crucial carbon price signal [13].

Structural Deficits in MRV

The most significant weakness in China's national carbon market remains the MRV system—the processes governing how emissions are measured, reported, and verified. While China has established national standards, implementation quality varies substantially across provinces and companies [14]. Some firms rely on manual records, rough estimates, or default emission factors instead of site-specific measurements, and verification capacity is not always strong enough to catch problems consistently. This leads to emissions data that can be noisy, inconsistent, and sometimes hard to trust. When the data itself is uncertain, regulators struggle to supervise effectively, market participants lose confidence in compliance claims, and the carbon price signal becomes weaker and less reliable for guiding real investment in emissions reduction [15].

Non-Standardization and Error Propagation: Many regulated entities, especially those with diverse operational profiles, still rely on varied or inconsistent methodologies for estimating emissions. The core issue often involves the emission factor, which is the coefficient used to convert activity data (like fuel consumption) into CO_2 .

The fundamental calculation for an entity's annual emissions (E) is:

$$E = \sum_{i=1}^N (AD_i \times EF_i \times O_i) \quad (1)$$

where AD_i is the activity data (e.g., mass of coal burned), EF_i is the emission factor for that fuel or process, and O_i is the oxidation factor (efficiency of combustion).

In practice, the values EF_i used often stem from default national averages rather than facility-specific measurements, introducing a systematic error ϵ_{EF} . Furthermore, reliance on manual monitoring and record-keeping introduces a stochastic error ϵ_{AD} in the activity data. The total reported

emission $E_{reported}$ therefore diverges from the true emission E_{true} by a significant margin:

This ϵ_{total} (total reporting error) is unevenly distributed across the market, making it impossible for the regulator to accurately assess the total market-wide emission level (the Tonnage Cap) [16].

The Verification Capacity Constraint: The third-party verification process, which is designed to validate $E_{reported}$, faces severe logistical limitations. With over 2,500 entities currently covered (primarily in the power sector), ensuring exhaustive, high-quality audits is constrained by the limited pool of certified and experienced verifiers. This lack of robust oversight creates a system where verification quality itself becomes heterogeneous across provinces, leading to a compliance probability P_C that is less than one for inaccurate reports, fostering a moral hazard among non-compliant firms [17].

Information Asymmetry and Market Efficiency

The existence of a significant reporting error (ϵ_{total}) translates directly into market failure through the mechanism of information asymmetry. This refers to a situation where one party (the enterprise) possesses superior knowledge about its true compliance status and costs than other parties (the regulator or investors). The initial statement: The existence of a significant reporting error translates directly into market failure through the mechanism of information asymmetry [18]. This information gap is the root of the market's problems because it gives companies a massive advantage and incentive to "game the system" from the very start. Since regulators cannot perfectly or continuously monitor every emission source, enterprises exploit the weaknesses in the auditing rules known as the MRV protocols which often rely on intermittent checks or easily manipulated manual inputs rather than tamper-proof CEMS [19].

This institutional failure empowers companies to engage in strategic manipulation. They can intentionally under-report their current pollution or exaggerate their historical emissions baselines when the cap-setting authority is determining future allowance limits. This intentional data distortion immediately results in the government handing out too many free pollution permits (chronic over-allocation). When the market is flooded with this excess liquidity, the allowance price is artificially suppressed and remains chronically low. This prevents the carbon price from ever reaching the crucial level needed to force reluctant companies to make difficult, large-scale, and necessary capital investments in decarbonization technology [20]. Ultimately, this pervasive lack of trustworthy data not only undermines the market's efficiency but also creates a moral hazard: why spend money to verifiably reduce pollution when the probability of being caught and penalized for non-compliance is low? The cycle ensures the entire market loses its power and policy purpose as a tool for driving serious, cost-effective climate action, hindering progress toward national neutrality goals.

Adverse Selection in Allowance Allocation: The regulator Ministry of Ecology and Environment (MEE) relies on historical $E_{reported}$ to set the initial allocation of allowances (the Grandfathering or Benchmark method). If enterprises

consistently over-report their historical emissions in anticipation of a loose cap, the system suffers from adverse selection.

Let $A_{allocated}$ be the number of allowances allocated to a firm. If the allocation is based on a benchmark (B) and historical reported emissions ($E_{reported}$):

$$A_{allocated} = B \times E_{reported} \quad (2)$$

This mechanism weakens market scarcity and undermines the incentives effect of carbon pricing.

Hindered Price Discovery and Liquidity: The lack of standardized and publicly accessible emissions data creates a fundamental block that prevents the carbon market from evolving into a powerful financial force. Think of it this way: investors and banks hate surprises. When emissions reports are inconsistent, delayed, or subject to suspected manipulation, financial institutions can't accurately model the future compliance risk of the companies they might lend to or invest in. This data opacity casts a permanent shadow of doubt over the entire system. Because this perceived risk is so high and the financial fundamentals are so blurry, sophisticated players like large institutional investors or hedge funds simply stay away [21]. They can't perform the speculative, forward-looking trading or the long-term hedging activities that are essential for injecting deep liquidity and financial momentum into a market. Consequently, the carbon market remains stuck as a rudimentary 'compliance-only' mechanism. Companies participate only because they have to meet the bare minimum regulatory obligation, rather than seeing the carbon allowance itself as a stable, valuable financial asset [22]. This cycle ensures the market never develops the strong, predictable price signals needed to truly drive billions in long-term capital towards green technology innovation.

Distortion of the Carbon Price Signal

The final consequence of informational risk is the failure to establish an efficient carbon price (P_{carbon}) the central function of an ETS. The price should ideally reflect the MAC across the economy.

Weak Price Signal: Due to the combination of perceived over-allocation (driven by asymmetric information) and weak enforcement ($P_C < 1$) the equilibrium price of carbon in the China's National Carbon Market often remains significantly below the estimated Social Cost of Carbon (SCC) and the actual MAC for deep decarbonization investments.

Impact on Investment: Companies determine their investment in abatement technology ($I_{abatement}$) by comparing the cost of compliance (buying allowances) versus the cost of abatement. They invest when:

$$I_{abatement} \leq P_{carbon} \times (E_{true} - E_{new}) \quad (3)$$

where E_{new} is the new, lower emission level. When P_{carbon} is low and unstable due to data issues, the inequality is rarely met, leading to delayed or insufficient investment in transformative low-carbon innovation, thus jeopardizing China's 2060 carbon neutrality goal.

These intertwined risks demonstrate that digitalization and improved data governance are not just technical upgrades, but structural prerequisites for establishing a functional, credible, and climate-effective carbon market.

TECHNOLOGY-DRIVEN SOLUTIONS: BUILDING A SMART CARBON MARKET (2015–2025)

Having established that the current system's reliance on outdated, manual processes introduces significant and quantifiable informational risks, Section 4 pivots to the solution: a complete digital transformation. This analysis is grounded in the rapid advancements of China's digital economy over the last decade (2015–2025), proposing that the strategic integration of Blockchain, AI, and the IoT is the essential lever to transform the China's National Carbon Market from a vulnerable, fragmented market into a verifiable, market-effective instrument capable of delivering China's 2060 carbon neutrality goal [23].

Forging a Trustworthy Data Foundation: Blockchain and IoT for MRV

The most critical task is to eliminate the fundamental reporting error (ϵ_{total}) that compromises market fairness. Digital technologies achieve this by automating data capture and creating an immutable record.

The Shift to Real-Time Monitoring via IoT: The deployment of Industrial IoT and enhanced CEMS, spurred by national mandates since the 13th Five-Year Plan, is key. These sensors replace fallible human record-keeping with direct, automated data streams, capturing real-time activity data (AD_i) and emissions rates.

Analysis: This automation facilitates continuous compliance auditing, a major leap from the current annual review cycle. By minimizing the time and space for manipulation, the system dramatically increases the chance of detecting fraudulent reports. In economic terms, this increases the perceived compliance probability (P_C) toward 1, thereby extinguishing the moral hazard that currently rewards non-compliant firms [24].

Realistic Example: Instead of relying on a firm's monthly ledger, the system pulls instantaneous, verifiable data from factory smart meters and stack sensors, providing an unedited, objective record of environmental performance.

Guaranteeing Integrity with Enterprise Blockchain: Drawing on the rapid development of sovereign enterprise blockchain platforms in China, this technology provides the essential distributed, immutable ledger for emissions data and allowance transactions.

Analysis: When final verified emissions data ($\hat{E}_{true}$) are housed on a blockchain, they become cryptographically secured and tamper-proof. This assurance directly mitigates the risk of Adverse Selection (Section 3.2.1), preventing firms from manipulating historical data to secure an undeserved windfall of allowances (A_{excess}). The entire allocation and retirement process becomes an auditable chain of custody, dramatically bolstering external investor confidence. [25]

Mechanism: An allowance unit, tokenized and recorded on the ledger, is linked to a cryptographic hash (H). Any attempt to alter the verified emission data ($\hat{E}_{true}$) that determined its allocation would invalidate. This transforms the regulator's burden of trust into a function of computational verification [26].

Dynamic Oversight and Policy Optimization with AI and Big Data

With a reliable data foundation in place, AI provides the intelligence layer needed to manage the market's complexity, specifically by stabilizing the crucial carbon price (P_{carbon}).

Algorithmic Enforcement and Anomaly Detection: Leveraging the maturity of AI in China's FinTech sector (post-2016), Machine Learning algorithms can process vast, high-frequency data streams to monitor market health.

Analysis: AI can analyze complex trading, emissions, and energy consumption datasets to detect anomalous behavior indicative of manipulation or intentional under-reporting. Unsupervised learning models can instantly flag entities whose performance deviates statistically from industry norms, transforming oversight from a slow, reactive process into a proactive, real-time enforcement system. This increases the speed and certainty of regulatory response [27].

Data-Driven Market Stabilization (MSR): Big Data and predictive AI modeling enable regulators to move away from static, rigid policies to dynamic, evidence-based interventions a core feature of global best practices.

Dynamic Policy Framework: By employing Time Series Forecasting and Dynamic Stochastic General Equilibrium Models, fueled by real-time data, regulators can accurately estimate the forward-looking marginal abatement cost MAC and forecast allowance surpluses.

MSR Optimization: An AI-informed MSR can be optimized to stabilize prices by minimizing the deviation between the observed carbon price (P_{carbon}) and the target SCC over time (T). This ensures the market delivers the correct economic signal:

$$\min_Q E \left[\sum_{t=1}^T [P_{carbon,t} - SCC]^2 + \lambda \cdot \text{Penalty}(P_{carbon,t} < P_{floor}) \right] \quad (4)$$

where Q is the allowance quantity managed by the MSR, and λ represents the penalty weight associated with carbon prices falling below the minimum floor price (P_{floor}). This proactive management approach is essential, as it helps reduce excessive price volatility and guides the observed carbon price closer to the target social cost of carbon over time. By stabilizing price expectations, the mechanism strengthens market confidence and supports consistent investment signals, thereby contributing to the effective functioning of the carbon market and the achievement of China's long-term decarbonization objectives.

Strategic Prerequisites for Digital Transition

Realizing this smart market vision requires national-level policy and investment decisions:

Standardized Digital Architecture: A federal mandate for unified data protocols is essential to ensure seamless interoperability between all provincial systems, industrial CEMS, and the central digital platform.

Investment and Talent: Targeted government and private investment must upgrade industrial infrastructure and establish extensive training programs. This ensures the availability of the skilled technical workforce required to manage and operate these complex, sophisticated AI/Blockchain ecosystems. The integration of these technologies represents the most significant opportunity for China to overcome the systemic risks of its nascent carbon market and validate its role as a leader in global climate governance [28].

POLICY COORDINATION AND REGULATORY ENHANCEMENTS (2015–2025)

The technological transition outlined in Section 4 while essential for improving data integrity, transparency, and market efficiency cannot succeed on its own unless the China National Carbon Market also addresses the deeper regulatory risks that continue to shape market outcomes. These risks are not simply technical weaknesses; they stem from institutional and governance arrangements, especially the fragmented regulatory landscape that emerged during the pilot phase (2013–2020). Although decentralized experimentation enabled regional learning and flexibility, it also produced uneven enforcement practices, overlapping administrative responsibilities, and inconsistent policy interpretation across jurisdictions. As a result, enforcement can remain weak in practice, regulatory signals may appear mixed, and penalties for non-compliance do not always generate a strong and predictable deterrent effect.

Experience over the past decade indicates that moving toward a genuinely "Smart Carbon Market" requires more than deploying digital monitoring tools or advanced analytics. It also requires a stronger and more coherent regulatory commitment, reflected in clearer national oversight, better coordination among responsible agencies, and more consistent rules and procedures across regions. Such institutional alignment is critical for ensuring that technological systems are trusted by market participants and that compliance is viewed as fair, predictable, and credible. In this sense, technology and regulation are interdependent: without robust governance, digital solutions risk being treated as formalities rather than drivers of real change, while effective regulation increasingly depends on digital infrastructure to function reliably at scale and with precision.

Unifying the Legal Framework and Policy Commitment

A critical risk factor is the historical fragmentation of legal authority; prior to the State Council's 2024 "Interim Regulations", the market was largely governed by Ministerial-level administrative measures from the MEE, which limited the scope of penalties and regulatory reach.

Analysis: Regulatory certainty is the bedrock of long-term abatement investment. The legal elevation of the ETS framework to the State Council level (starting May 2024) is a pivotal step. It formalizes a multi-departmental cooperation mechanism, involving key bodies like the National Development and Reform Commission and regulatory

commissions. This shift minimizes the risk of inter-agency conflict that previously allowed non-compliant firms to exploit regulatory grey areas between central environmental mandates and local economic development priorities [28].

Data and Context: The regional pilot markets, active since 2013, operated with varying penalty regimes. For instance, early MEE-level rules often capped administrative fines for non-compliance at a non-deterrent level (e.g., Chinese Yuan (CNY) 30,000 in some pilots), which was negligible for large State-Owned Enterprises (SOEs). The 2024 regulations directly address this by setting penalties for failure to surrender allowances at 5 to 10 times the market value of the gap, a significant, quantifiable increase in deterrence.

$$D_{new} = [5, 10] \times P_{carbon} \times E_{gap} \gg D_{old} \approx \text{CNY}30,000 \quad (5)$$

where D is the penalty, E_{gap} is the emissions shortfall, and the new rule dramatically elevates the deterrence cost (D_{new}).

Strengthening Enforcement and Mitigating Local Protectionism

The most persistent regulatory risk is the credible enforcement gap: enforcing ETS mandates against powerful local SOEs often the largest compliance entities and key emitters is politically and administratively difficult because these firms are frequently treated as strategic assets for regional economic growth, employment stability, and energy security. In practice, this can create a classic principal-agent problem in which local authorities have incentives to soften enforcement, tolerate incomplete compliance, or apply penalties inconsistently to avoid short-term economic or social costs. When the expected cost of non-compliance is perceived as low—due to discretion in inspections, uneven verification capacity, or weak sanction credibility firms may rationally delay abatement, and the market's overall credibility and price signal can be undermined.

Penalizing Data Fraud and Service Providers: The technological advancements in Section 4 (Blockchain, AI) are only effective if the penalties for attempting to compromise them are severe. The new regulatory framework (post-2024) specifically targets third-party verification firms and consultants involved in data fraud, which was a significant issue in early compliance cycles [7].

Analysis: By introducing penalties of up to 10 times their illegal gains and the cancellation of business qualifications, the State Council regulations are establishing accountability for the technical service sector. This is a crucial policy mechanism that complements technological solutions: while Blockchain provides integrity, the regulatory framework must enforce the penalty for trying to break it.

Example: If an AI detection system flags statistically impossible emissions reports (Section 4.2.1), the new regulatory teeth ensure the consequence is economic destruction, not just a slap on the wrist.

Transitioning to Absolute Cap and Auctioning: To inject necessary scarcity and address the risk of allowance over-allocation (fueled by $E_{reported}$ manipulation), the regulatory design must accelerate the transition away from its current intensity-based cap towards a binding absolute cap system.

Analysis: While China initially used an intensity-based system (emissions per unit of output) to safeguard economic growth during the 14th Five-Year Plan (2021-2025), a commitment to an absolute cap by 2030 is crucial for achieving carbon neutrality. Simultaneously, the current system of 100% free allocation must be gradually phased out by introducing allowance auctions. Auctions allow the market to determine the true carbon price and provide the MEE with revenue for a Green Transformation Fund to support low-level regions, addressing a key equity concern.

Realistic proposal: China should aim for an allowance auctioning share of at least 25% by 2030 to begin aligning domestic carbon prices (currently around 11 per tCO₂) with international benchmarks, thereby strengthening the competitiveness of the China national carbon market and helping to deter carbon leakage under mechanisms such as the European Union's Carbon Border Adjustment Mechanism (CBAM).

Policy Mandates for Digital Integration

The final enhancement concerns the policy framework required to effectively mandate, coordinate, and leverage the technological solutions discussed in Section 4. While technological innovations provide the necessary tools for improving market transparency, monitoring accuracy, and risk management, their impact remains limited without a coherent and enforceable policy architecture. A well-designed policy framework plays a crucial role in translating technological potential into practical outcomes by establishing clear regulatory standards, defining institutional responsibilities, and creating incentives for adoption and compliance. Moreover, such a framework helps align the interests of market participants, regulators, and technology providers, ensuring that technological deployment supports broader climate objectives rather than functioning in isolation. In this sense, policy is not merely a supporting condition but a central mechanism that enables technological solutions to operate at scale and deliver sustained improvements to the carbon market system [7].

Mandatory Digital MRV: Policy should require large industrial emitters (e.g., above 100,000 t CO₂/year) to adopt CEMS/IoT for emissions monitoring by a fixed date (e.g., end of the 15th Five-Year Plan, 2030).

National Data Protocol: The MEE must promulgate a national standard for data architecture and transmission protocols (analogous to national FinTech standards) to ensure that data captured by disparate IoT/CEMS systems is immediately readable by the central AI/Blockchain registry. This eliminates fragmentation at the technical level.

Regulatory Mechanism Formalization: The MEE should formally define the precise quantitative triggers for the MSR mentioned in Section 4.2.2. These rules must be transparent, non-discretionary, and legally binding to increase investor confidence in price stability.

In conclusion, the effectiveness of China's digital carbon market depends not simply on the availability of technology, but on the political will to enforce unified, high-deterrence regulation a shift that recent State Council actions suggest is occurring.

DISCUSSION

The synthesis of our analysis confirms that the persistent underperformance of China's National Carbon Market indicated by the low, volatile carbon price (P_{carbon}) is fundamentally a crisis of institutional credibility rather than a mere technical market failure. This crisis originates from a self-perpetuating cycle where the historical reliance on manual MRV created systemic Informational Risk (ϵ_{total}). This reporting uncertainty, when coupled with a legacy of weak enforcement ($P_C \ll 1$) characteristic of the pilot era, fostered a detrimental compliance cognitive bias in regulated firms, as predicted by behavioral economics: the perceived benefit of gaming the system outweighed the minimal penalty for non-compliance. This sustained behavioral failure led to the Adverse Selection that guaranteed structural oversupply ensuring the price signal remained decouple (A_{excess}) and suppressed P_{carbon} from the true SCC. The pathway to unlocking the China's National Carbon Market's potential therefore requires breaking this cycle by applying a synergistic dual solution that addresses both the technical and behavioral failures: technology must provide the objective truth, and regulation must enforce the necessary consequence [29].

The core of this dual solution lies in establishing a system of uncompromising credibility through the strategic integration of advanced digital platforms. The mandatory deployment of Industrial IoT and CEMS ensures real-time, automated data streams, thereby eliminating the systemic reporting error (ϵ_{total}). Crucially, the use of Enterprise Blockchain transforms emissions data ($\hat{E}_{true}$) into an immutable, cryptographically verifiable asset, shifting data integrity from a matter of *trust* to a matter of *certainty*. However, this technological backbone is only effective when paired with decisive policy: the regulatory elevation of penalties (D_{new}) and the formalization of the MSR mechanism are the necessary complements. This integrated approach where technology enables detection certainty and policy imposes financial ruin is essential to reset the market's behavioral equilibrium, ensuring that compliance becomes the economically rational choice. Furthermore, AI-driven oversight enhances regulatory capacity by employing algorithms for anomaly detection and optimizing the MSR through forecasting, transforming market stability from a political reaction into a transparent, data-driven calculation [29,30].

Beyond optimizing conventional industrial compliance, this digital framework opens critical frontiers for the China's National Carbon Market's evolution and global relevance. Firstly, it facilitates the essential expansion into Nature-based Solutions (NbS), as the IoT and Blockchain infrastructure can be leveraged to track soil organic carbon and verify long-term sequestration, thereby mitigating the severe non-permanence and leakage risks currently hindering NbS credit integrity. This strategic expansion allows China to secure crucial, cost-effective offsets to meet its 2060 commitment by utilizing its vast natural capital. Secondly, the successful transition to a verifiable, high-integrity market carries significant geopolitical weight. By strategically raising its domestic carbon price and establishing an internationally credible verification standard, China strengthens its position against emerging trade barriers like the CBAM. As the world's largest ETS in an emerging economy, the China's National Carbon Market provides a transferable governance model one that demonstrates how state

capacity, technological innovation (guided by principles of digital ethics to ensure fairness and transparency), and market mechanisms can be synchronized to achieve ambitious decarbonization goals, providing crucial leadership for the Global South [30].

Conclusion

This research established that the underperformance of China's National Carbon Market evidenced by the persistent low carbon price and insufficient abatement investment is not a simple economic setback but a profound crisis of institutional credibility. Our analysis conclusively demonstrates that this crisis originates from a vicious cycle where Informational Risks, stemming from a decade of reliance on outdated, manual MRV protocols, enabled systemic data manipulation. This structural reporting error then coupled with Regulatory Risks, where weak legal enforcement and negligible penalties failed to deter fraud. This combination effectively nullified the market's price signal, ensuring polluting remained cheaper than innovating. The China's National Carbon Market, therefore, cannot achieve its ambitious 2060 carbon neutrality goal unless it decisively breaks this cycle through the synergistic implementation of a dual regulatory-technological framework. The future success of this market hinges on establishing an uncompromising environment where technological certainty provides the objective truth and decisive policy ensures the necessary consequence. The core of our policy recommendation centers on three urgent, strategic mandates designed to reset the market's behavioral and structural equilibrium. First, the MEE must issue a non-negotiable decree for the mandatory installation of CEMS/IoT and compliance with a new national digital data protocol by 2030, transforming emissions data into an immutable, verifiable asset. Second, policy must guarantee market certainty by formally defining the rules for the MSR, making its AI-driven adjustments transparent and binding to provide the long-term price confidence investors demand. Third, the MEE must commit to an irreversible transition to a binding absolute cap by 2030 and rapidly increase the auction share to at least 25%, as injecting genuine scarcity is the only path to raising the carbon price high enough to align with global climate ambitions. These actions, enforced by the elevated legal authority of the State Council and severe financial penalties, represent the critical operational steps required to unlock transformative capital.

Finally, while our framework offers a detailed blueprint for structural enhancement, its implementation necessitates continued academic scrutiny. Future empirical work is crucial, requiring access to proprietary, high-frequency trading data to precisely model the real-time volatility dampening effects of the AI-MSR system. Furthermore, research must expand the application of this dual framework to the specific technological and enforcement challenges of newly included high-emitting sectors like steel and cement. By successfully digitalizing its market and integrating advanced governance principles, the China's National Carbon Market not only secures China's path toward its 2060 commitment but also establishes a transferable, scalable blueprint for cost-effective climate governance in other rapidly developing economies worldwide, cementing its position as a global leader in climate solutions.

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