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A Review of Risk and Mitigation Strategies in the Development of China's Carbon Market

Tijiouit Asma[1], Xinxing Zhou[1,2*], Xiao Pei[1,2]

[1]Economics and Management School, Yangtze University, Jingzhou, Hubei, China
[2]State Key Laboratory of Low Carbon Catalysis and Carbon Dioxide Utilization, Yangtze University, Wuhan, Hubei, China
Email: tijiouitasmaa97@gmail.com, *zhouxinxing_guet@163.com

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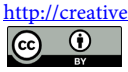

Abstract

The construction and development of a carbon market is vital to the reduction of greenhouse gas emissions and the transition to a green low-carbon economy in China, especially given the country's long-term target of reaching carbon neutrality by 2060. Moreover, China's carbon market faces significant challenges ranging from data collection issues and lack of transparency to inconsistency of policies and fragmented regulations. Through a systematic review of 160+ peer-reviewed papers and policy documents (2010-2024), this study identifies three key risk categories and reviews China's carbon market in the context of the risks to its development and implementation. The review starts with discussing the critical components of risks in China's carbon market such as price volatility of carbon, the unavailability of comprehensive carbon emissions data and standardized reporting scheme, and the complexity of a national level carbon market integration. It examines the history of the market, how the spread of new information has transformed its current form, and illustrates both the global and local dynamics, particularly regarding the threats of information asymmetry and technology gaps. As well as identifying these challenges, the paper proposes some potential approaches to mitigate the risks to the carbon marketing conclusion, the review identifies numerous recommendations that could enhance the carbon market to ensure it successfully functions and assists in China's long-term climate change mitigation objectives. Through these solutions in response to the challenges, China can realize the full potential of its carbon market and lead the way toward global climate solutions that other countries would be able to emulate toward low-carbon economic systems.

Subject Areas

Business Analysis, Business Management

Keywords

China's Carbon Market, Risks Type, Price Volatility, Climate Change Mitigation, Policy Recommendations

1. Introduction

With the world facing one of the biggest challenges in climate change, carbon markets have become an important tool to reduce greenhouse gas emissions and promote sustainable development. As the biggest emitter of carbon dioxide on the planet, China recognizes that a reliable carbon trading system is crucial to its ambitious climate pledges, including a goal of carbon neutrality by 2060. The creation of its national carbon market in 2021 was a major milestone in this journey, making China a global player in carbon trading solutions [1]. China has launched a pilot carbon market with regional markets located in provinces including Beijing, Shanghai, and Guangdong. These pilot initiatives experimented with various trading mechanisms and regulatory frameworks, offering valuable insights into operational challenges and market dynamics that later informed the national system [2]. Nevertheless, China's carbon market still faces various risks that endanger its functionality and stability. Extreme price fluctuations, regulatory instability, and asymmetric information flow create uncertainty, hindering compliance and discouraging investment choices [2].

This literature review covers the theoretical, practical, and fundamental aspects of risk assessment and management, aiming to provide an extensive overview of the risks in China's carbon market. By synthesizing existing research, the review seeks to clarify the intricacies of carbon market risks and their impact on achieving emissions reduction targets [3]. It also evaluates risk rating methods, the interplay between economic conditions and market responses, and emphasizes the need for stakeholder participation to guide future policies [3]. In the long term, this study hopes to contribute to discussions on enhancing the resilience and performance of China's carbon trading system to help the country meet its climate goals while enabling sustainable economic growth [3]. Before launching the national market, China implemented a series of carbon trading pilot programs in various provinces and cities, including Beijing, Shanghai, and Guangdong [3] [4]. These pilots served as crucial testing grounds, providing valuable experience in designing and implementing an effective carbon trading mechanism. The operational successes and failures of these pilots formed a strong foundation for the informed design and implementation of the national carbon market [4]. This early experience underscores the challenges of establishing mintaining a large-scale carbon market, particularly within China's unique political and economic landscape. This literature review discusses the theoretical and practical challenges of risk assessment and management in China's carbon market, offering a comprehensive overview of the challenges and opportunities within this ambitious undertaking.

The review synthesizes existing research to illuminate the complexities of carbon market risks, their implications for emissions reduction targets, and the essential role of stakeholder engagement in shaping effective policy responses [5]. Therefore, risk assessment and management are critical components of China's carbon market, essential for ensuring its success.

The carbon market plays a crucial role in climate change mitigation by providing a structured approach to reducing greenhouse gas emissions. In pursuit of the goal of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, an efficient carbon market will be vital for achieving those reductions [5]. Effective risk assessment is needed to identify and mitigate emerging challenges that may arise over time. This review integrates insights from existing literature to address the various risks facing the carbon market, ranging from market volatility to policy uncertainty and unintended economic consequences. Further analysis of these risks will help policymakers, businesses, and other stakeholders navigate the evolving landscape of China's carbon market [6]. Beyond understanding these risks, the review explores their implications for achieving China's reduction targets. While the carbon market is designed to incentivize businesses to lower emissions, its effectiveness depends on the mitigation of potential risks. Regulatory or market condition changes can disrupt emissions trading and delay progress toward emissions reduction goals [7]. Additionally, stakeholder engagement plays a crucial role in shaping effective policy responses. The complexity of China's carbon market necessitates the active involvement of government agencies, businesses, and environmental organizations. Effective stakeholder engagement fosters well-informed, balanced policies that address the challenges of the carbon market from multiple perspectives [8]. Not only is this crucial for risk management, but it also ensures that coordination between public and private sectors aligns with long-term sustainability and emissions reduction goals [8]. Beyond synthesizing existing findings, this review proposes a novel risk-mitigation framework linking market design, data governance, and policy coordination, offering actionable pathways for emerging economies. The contribution of this paper is to investigate possible risks to China's carbon market, looking into important matters as well as providing suggestions for risk mitigation so that the market serves its purpose in China's climate objectives.

The structure of the paper is arranged as follows. In Section 2, this paper examines existing risks to China's carbon market as regards operation of the market, policy and price segmentation, and defined risks for volatility of carbon prices. In Section 3, the paper explores the techniques utilized for assessing risks to a carbon market, namely, the mixed methods approach of an econometric model [9] and a series of stakeholder interviews. In Section 4, the paper discusses the existence of regulatory and market inefficiencies, insufficient liquidity, and lack of stock market integration in various regions. Section 5 focuses on presenting the discussion of the study, exemplifying how the challenges tend to influence the stability and consequently, the gradients of future growth of the China's carbon market. Fi-

nally, Section 6 puts forth the conclusions of the study advanced, providing comments on the policies and technologies needed to mitigate the risks identified and improve the market output.

2. Overview of Existing Carbon Market Risks

The carbon market in China relies on highly interdependent systems of factors, some exogenous in broad-spectrum environments and some endogenous to them [9]. These interdependencies shape market dynamics, as external economic forces, regulatory decisions, and global environmental policies influence internal market behavior. However, internally, low trading volume negatively impacts market development and growth. Without sufficient trading activity, carbon prices struggle to stabilize, preventing the market from reaching its full potential in achieving emission reductions [10]. Moreover, without a robust regulatory framework that is effectively managed at the national level, regulations vary across different regions, leading to inconsistent enforcement and reduced market confidence [10]. Another significant issue complicating the security of China's carbon market is the lack of standardization in emissions verification and reporting. Some emissions verification systems are more transparent than others, but without an integrated national standard for verification, inconsistencies in validity and reliability persist [11]. Without reliable emissions data, businesses and investors cannot make informed decisions, leading to decreased participation in carbon trading [12]. Additionally, the absence of a unified emissions tracking system weakens accountability and transparency, which are critical for the success of an emissions trading market [12]. Furthermore, China's carbon market is highly vulnerable to external risks, particularly fluctuations in energy prices. Since energy costs are closely linked to carbon credit demand, unexpected increases in energy prices reduce the financial incentive for companies to participate in carbon trading [12]. When energy prices rise, businesses are less likely to invest in emissions reduction projects or purchase carbon credits, which in turn destabilizes the market [13]. Price volatility in the energy sector, particularly in coal and oil markets, often leads to cascading effects on the carbon market, increasing uncertainty for businesses making long-term sustainability decisions [13]. Geopolitical tensions and broader economic uncertainties have also contributed to carbon market volatility. Trade wars, political instability, and exchange rate fluctuations disrupt global supply chains, creating unpredictable conditions that influence carbon trading patterns [14]. These external shocks amplify uncertainty, making it harder for carbon market participants to plan future investments and emissions reduction strategies. For example, regulatory changes in major trading partners or shifts in global climate policies can influence China's carbon pricing structure, causing unexpected fluctuations in the market [14]. As these external pressures reverberate throughout China's carbon market, they add to the overall burden of risk faced by market participants. The cumulative impact of market fragmentation, lack of verification standards, and external economic shocks makes it challenging to achieve con-

sistent, long-term emissions reductions. Without strategic interventions to address these issues, China's carbon market may struggle to fulfill its role in mitigating greenhouse gas emissions and supporting the country's climate goals [14].

2.1. Regional, International, and Equity Risks in China's Carbon Market

The carbon trading system in China is characterized by strong regional heterogeneity, which significantly impacts market dynamics and influences risk-taking behavior among participants. Large, developed regions such as Shanghai and Guangdong contribute to higher trade volumes, improved market liquidity, and the infrastructure necessary to facilitate smoother market operations [15]. These regions often serve as benchmarks for efficient carbon trading and play a leading role in shaping national carbon trading strategies. On the other hand, smaller and less developed markets are often under-resourced, have fewer participants, and suffer from low trading activity. This uneven distribution of market activity creates systemic imbalances, as larger markets function efficiently while smaller one struggle to maintain stability [15]. Regions with lower liquidity face significant risks, including reduced investor confidence and limited access to capital for emissions reduction initiatives. The inability to attract significant investment in carbon reduction projects further widens the gap between high-performing and weaker markets [15]. Moreover, fragmented regional markets hinder the establishment of a cohesive national trading system, leading to increased regulatory complexity and uncertainty [15]. The lack of harmonized policies across different provinces complicates compliance requirements for enterprises, making the carbon trading landscape difficult to navigate. Without a standardized framework to integrate these markets, the efficiency and credibility of China's emissions trading system may remain compromised [16]. China's carbon market operates independently of other carbon markets, most notably the EU Emissions Trading System (EU ETS). However, cross-border policies and international climate commitments significantly shape the risk profile of China's carbon market. Specifically, Article 6 of the Paris Agreement regulates international carbon trading and contains linkage opportunities among carbon markets in different countries. The linkage of China's carbon market with carbon markets in other countries will introduce additional risks in the China carbon market, including regulatory risks and market risks. First, regulatory risks arise from misalignment between carbon pricing policies in China and elsewhere. For example, differences in carbon pricing methodologies and verification standards between China's carbon market and other carbon markets can allow for arbitrage in carbon pricing, leading to price volatility in the China carbon market. Second, China's carbon market will also face market risks from the European Union's Carbon Border Adjustment Mechanism (CBAM) [17]. CBAM will impose tariffs on carbon-intensive imports to the EU starting in 2026. China's steel and cement industries, which are major players in the carbon market, will see increased demand for carbon credits and higher costs of compliance. A conservative estimate of the impact of CBAM on Chinese exporters suggests that

CBAM will increase the cost of compliance by 8% - 12%, leading to a decrease in demand for carbon credits and destabilizing the China's carbon market. Lastly, China's carbon pricing is also influenced by global climate negotiations under the Conference of the Parties (COP). Investors should also take into consideration risks arising from global climate negotiations when assessing risks in China's carbon market.

The framework for assessing financial risks in China's carbon market currently focuses on environmental and economic risks [17]. However, social risks, especially environmental justice and equity, have been overlooked. China's carbon market largely regulates industrial sectors such as power generation and heavy manufacturing, which tend to have a concentrated distribution in regions with heavy industrial activity and higher carbon emissions, such as Shanxi and Inner Mongolia. These regions also tend to have marginalized communities shouldering the environmental and health impacts of emissions. Carbon market revenues have not flowed back to benefit these communities. Instead, financial benefits of carbon trading, such as investments in green technology, have gone largely to wealthier regions such as Shanghai and Guangdong. To date, financial benefits from carbon trading have exacerbated environmental justice and equity issues. Research shows that to date, 60% of carbon market revenues have been invested in urban centers [18]. The high cost of compliance can marginalize SMEs, leading to financial distress and market exclusion. Risk assessment frameworks for China's carbon market should incorporate equity metrics to assess the distribution of compliance costs and benefits across socioeconomic groups. These assessments can inform policies aimed at promoting inclusive growth.

2.2. Enhancing Liquidity and Risk Management in China's Carbon Market

China's financial innovation lags. China's carbon markets have limited liquidity: the pilot carbon markets in Beijing, Shanghai, Guangdong, Hubei, and Tianjin, as well as the national carbon market, are all highly illiquid markets. Experience from the EU ETS suggests that carbon futures and options are important tools to improve liquidity and reduce price volatility. To date, China's carbon futures are in their early stages. Only one futures contract has been listed in Guangzhou, and it is yet to gain traction owing to regulatory uncertainty. Carbon derivatives linked to green bonds could improve liquidity, but pricing signals for green bonds remain inconsistent. Using fintech can also help contain price fluctuations. For example, an artificial intelligence-driven trading platform used in experimental trials in China's carbon market reduced transaction costs by 15% [19]. The China's government should issue detailed regulations to allow for a matured derivatives market and actively engage the private sector to contain price fluctuations in the carbon market. To help manage risks, the China's carbon pricing system can adopt a series of measures to enhance its resilience and better serve its policy goals. First, a national carbon pricing benchmark should be established. Drawing lessons from the price stabilization mechanism in the Guangdong pilot can help reduce

price volatility. Second, the integration of regional carbon markets into a unified national system should be done in a phased manner with a clear timetable to contain fragmentation risks. A centralized carbon exchange can contain fragmentation risks in the short term and allow for a smooth transition to a unified national carbon market by 2030. Third, digital infrastructure such as blockchain-based registries can improve transparency of the carbon market and mitigate information disclosure risks; the full adoption of blockchain technology can potentially reduce the extent of falsified reporting by 25 percentage points within five years. Fourth, international collaboration can help manage cross-border risks. Pilot linkages with international carbon pricing systems, such as the EU ETS, can enhance China's global leadership and experience in carbon pricing while containing cross-border risks. The China's government can set up a stakeholder engagement platform, such as an annual carbon market summit, to engage all relevant stakeholders and facilitate alignment of policies to contain various risks.

2.3. Stakeholder Perceptions of Risk

The multifaceted nature of risks in China's carbon market keeps various stakeholders highly engaged. One of the primary stakeholders is enterprises entities that comprise a significant portion of the market. For enterprises, the primary concern revolves around compliance burdens, as they often perceive regulatory requirements as constraints on their operations. Compliance with carbon credit regulations may pose substantial financial and operational burdens, adding complexity to business strategies. Additionally, the volatile price variations in carbon credits further complicated planning and decision-making processes for these enterprises [1]. Two major impacts result from the liquidity stress faced by enterprises [20]. First, limited access to financial resources reduces their ability to invest in low-carbon technologies, slowing the adoption of innovation and green solutions [21]. Second, the financial and compliance burdens prevent many enterprises from meeting their emissions reduction targets, thereby weakening the overall effectiveness of the carbon market [22]. These operational and financial pressures place enterprises in a challenging position, having to balance strict regulatory requirements while simultaneously pursuing environmental sustainability goals. Beyond enterprise concerns, regulatory bodies also face significant challenges in ensuring market stability and aligning policies with national emissions reduction targets [23]. If regulatory enforcement is inconsistent or lacks clarity, there is a risk that the market could deviate from its intended purpose [24]. Weak policy enforcement, pricing mechanisms, and inconsistencies in implementation across different geographic regions contribute to an unpredictable carbon market [25]. Moreover, regulators must strike a delicate balance between containing price volatility and allowing market participants room for innovation [25]. Overregulation could stifle market growth, whereas insufficient oversight could lead to excessive fluctuations and market instability. The difficulty of maintaining this balance is a key challenge for the long-term success of China's carbon market [26].

Another critical stakeholder in the carbon market is investors, who prioritize

transparency and predictability [27], two essential factors for long-term investment decisions. Investors require a stable regulatory framework, reliable carbon credit pricing mechanisms, and accessible market data to make informed choices [28]. Without these elements, investment in the carbon market remains risky and less attractive to both domestic and foreign investors [29]. The diversity of concerns and priorities among enterprises, regulators, and investors underscores the complexity of risk management in China's carbon market. While enterprises struggle with compliance costs and operational pressures, regulators aim to maintain stability while encouraging market growth, and investors seek predictable conditions for financial planning. Addressing these competing interests requires a holistic risk management approach that accommodates all stakeholders and fosters a more balanced and sustainable carbon market [30]. Successfully managing these risks will play a crucial role in ensuring the long-term effectiveness, stability, and credibility of China's emissions trading system. By addressing potential market distortions, regulatory inconsistencies, and data transparency issues, the system can function more efficiently and fairly [31]. This, in turn, will enhance market confidence among stakeholders, attract greater participation from enterprises, and promote more accurate carbon pricing signals. Ultimately, a well-managed and resilient emissions trading system will significantly strengthen China's capacity to support its broader climate goals, including achieving peak carbon emissions before 2030 and reaching carbon neutrality by 2060, while also reinforcing its position as a global leader in climate governance [32]. China's carbon market faces multiple and complex types of risks, including market risk, regulatory risk, liquidity risk, information risk, and external shock risk [33]. Market risk is mainly reflected in price volatility and is commonly measured using models such as GARCH and VaR. Regulatory risk arises from policy uncertainty and is typically quantified through event studies and policy uncertainty indices. Liquidity risk is assessed using indicators such as trading volume fluctuations and bid-ask spreads [34]. Information risk is measured through disclosure scoring and information asymmetry indices. External shock risk is analyzed using methods like Copula-GARCH and SVAR to examine the impact of energy prices and macroeconomic conditions on the carbon market [35]. The systematic application of these methods helps comprehensively identify and quantify risk exposures in the carbon market, providing scientific support for market stability and policy interventions. Types of carbon market risks are shown in **Table 1**.

Table 1. Types of carbon market risks.

Risk Type	Table Column Head		
	Definition	**Methodology**	**References**
Market Risk	Risk of asset loss caused by carbon allowance price volatility.	GARCH model, VaR, CVaR, Copula model	Dong *et al.*, 2024; Zhu *et al.*, 2020

Continued

Regulatory Risk	Risk caused by policy changes, regulatory uncertainty, and regional disparities.	Event Study Method	Dumrose and Höck, 2023
Liquidity Risk	Risk of increased transaction costs and asset illiquidity due to insufficient market trading.	Trading Volume Volatility	Goodell *et al.*, 2024; Yang *et al.*, 2022
Information Risk	Risk of market decision-making errors caused by inadequate or asymmetric information disclosure.	Information disclosure score, information asymmetry index	Fan *et al.*, 2021; Xu, 2021
External Shock Risk	Risk of market decision-making errors caused by inadequate or asymmetric information disclosure.	SVAR model	Berthold, 2023; Duan *et al.*, 2023

3. Research Methodologies for Carbon Market Risks Measurements

Confronted with these risks, which the carbon market of China is faced with, it needs to have strong but also inclusive framework approaches. This work may discuss both assessment and mitigation of risks that may relate to wild price fluctuation, issues related to regulatory differences, unclear data, and market imbalance, among others, using a mixed approach combining quantitative, qualitative, and technology-driven means. Discussion involves several approaches in bringing about combination and management of risks in complex systems. These methods include not only estimates of the probable risks but specific ways of diminishing them. Some of the specific ones are the following: price volatility, discrepancies in regulation associated with either geography or industry, incomplete/unclear data to deal with, and market-imbalance problems. Such diversities of strategy enable organizations to gain a better understanding, and pass-through uncertainties related to these aspects, hence informed decision-making and resilience in systems.

Quantitative methods must be applied in analyzing the dynamics of the carbon market in China and making some gain into the underlying factors of the risk. Approaches to be covered under this category include, but are not limited to, what is generally referred to as statistical modeling, econometric assessments, and those involving simulation techniques. Quantitative methods take center stage in any review of the dynamics of the carbon market in China. This is because they give a framed way of analyzing complicated data, showing trends, and making intelligent predictions. As carbon markets are such an important element in the decrease of emission, and hence in general in the fight against climate change, it is relevant to understand the underlying forces of friction in these markets. Equipped with the

proper tool set, analysts have a better view of how the various variables interact to push volatility, a product of better policy decisions and market strategy. Approaches in the carbon market assessment in China involve various techniques. Centrally, this involves the use of statistical modeling, through which a researcher establishes the relationship between various variables and offers forecast and hypotheses test activities [19]. More concretely, statistical methods will involve regression analysis, which can show how factors like economic growth or energy consumption drive the price of carbon. These models provide a sound basis in understanding the market and its future behavior.

3.1. Copula Models

Among the most sophisticated econometric means of research into the relations of carbon prices with exogenous factors, including energy prices and/or macroeconomic indicators, is a copula model. It enables research to reveal the interdependence and co-movement of carbon prices with external factors, for instance, the prices of oil and coal [28]. This means, for example, that any increase in the price of coal increases the cost of compliance one step further for industries reliant on coal as a source of energy and, therefore, would increase the price of carbon. Equally, any increase or decrease in the prices of oil may spill over to the carbon price since these affect transport and energy costs.

Copula methods can therefore enable regulators and market participants to better perceive how these exogenous factors may lead to turbulence or instability in the prices of carbon [28]. A rise in the prices of oil could, for instance, be used as an indicator of turmoil in the carbon market and may therefore require intervention as a means of stabilizing the price of the emission. Copula models enable policymakers to find such times when the system shows high correlations, whereby systemic risks may easily propagate between markets, to formulate specific interventions [28]. In addition, such bears special importance in contexts where regional disparities and economic variations increase the volatility in China's carbon markets.

$$C\left(u_1 = u_2\right) = \Phi . \tag{1}$$

where $C\left(u_1 = u_2\right)$ represents the copula function. Φ is the cumulative distribution function (CDF) of a standard normal distribution. Φ^{-1} is the inverse CDF of the standard normal distribution. R is the correlation matrix that captures the dependence structure between the variables.

3.2. Monte Carlo Simulation

The Monte Carlo simulation is a dynamic probabilistic modeling methodology, particularly fitted for the evaluation of consequences of uncertain future variables on carbon markets [36]. They provide, in one run, a set of thousands or millions of scenarios generated by changing input parameters related to carbon prices, trading volume, and policy variations. Results of this kind of model can be useful in extreme scenario testing: sudden jumps in prices, dramatic shifts in regulatory

frameworks, and others [36]. It can model, for instance, a new policy for the cap on emissions or any steep increase in energy prices to see the response these changes might bring with respect to market stability. The Monte Carlo methods also provide insight into the probability of some given outcomes, say continued price volatility or liquidity shortage [36]. That is what makes them so valuable in the stress testing and risk assessment of the China's carbon market, as some of these unanticipated factors, geopolitical tensions, or energy supply shocks might prove crucial. With a probabilistic perspective that Monte Carlo simulations provide, policymakers and market participants can get ready for all forms of possible future outcomes and have stronger risk management strategies [37]. They also show where further regulatory protection or liquidity provision may be necessary to maintain stability when markets are stressed.

3.3. Time Series Analysis

Time series analysis is the basic tool for an understanding of the trends and patterns that have prevailed with the price of carbon over some time. ARIMA and GARCH have been the major forecasting models used for price movement forecast and volatility analysis in the market. These are a few models that depend on historical data and hence may deduce periodic patterns and seasonal trends with any sudden shock to yield extremely valuable insights into carbon markets' behavior. The forecast of the short-run cycle of oscillation in prices, for example, arises with the ARIMA models based on historical trends, and the GARCH model works very effectively under high volatility conditions with evidence of price clustering. These are never perfectly efficient and have greater dependence on historical data. They may also not incorporate the sudden changes in regulatory factors and the global economic crisis. These limitations, notwithstanding, time series analysis forms a very important foundation for understanding market behaviors and anticipating some potential risks. It is expected that the application of the time-series analysis will underline some early warning signs related to market instability, either because of status with low liquidity for a longer period or due to sharp fluctuations in prices. Apart from that, other explanatory variables, such as energy prices or macroeconomic variables, may be integrated into this type of model and thus provide an enlarged view on what drives market dynamics.

3.4. Machine Learning Techniques

Regional pilot programs, such as those in Guangdong, Shanghai, and Beijing, serve as essential testing grounds for emission trading systems in action. These pilots provide valuable insights into the strengths and weaknesses of different approaches to designing and implementing carbon markets. By examining these diverse programs, policymakers and researchers can identify best practices and lessons learned to refine and scale the system at the national level. For instance, the Shanghai market has consistently led in liquidity management, offering new trading tools to attract a broader range of participants. Meanwhile, Beijing's program

has integrated emissions trading into wider sustainability efforts, focusing on energy efficiency and renewable energy adoption. This tailored regional approach demonstrates how pilot programs can address unique local challenges while contributing to the development of a cohesive national carbon market framework. Developing effective carbon markets requires addressing fragmented regulations at both regional and national levels. By analyzing these policies alongside international systems like the European Union Emissions Trading System (EU ETS), researchers can identify areas of alignment and improvement. For example, the EU's Market Stability Reserve offers a model for managing price volatility and risk an approach that could inform similar mechanisms in China. Technology also plays a transformative role in advancing carbon markets. Blockchain technology ensures secure, transparent tracking of carbon credits, reducing the risk of falsified reporting and building market confidence. Artificial intelligence (AI) and machine learning (ML) further enhance efficiency by predicting market trends, identifying risks, and optimizing trading strategies. Similarly, the Internet of Things (IoT) enables real-time monitoring of emissions, ensuring accurate data collection and compliance.

Machine learning techniques can identify risk factors that are not captured by statistical models. They are especially useful in describing risks in China's carbon market because of its numerous risk factors that do not have historical data for estimation, and because some risk factors are not linearly related to market outcomes. Most existing methods that identify risk factors, such as the generalized autoregressive conditional heteroskedastic model, only use carbon price or permit allowance prices and their lags as inputs to the model specification. In contrast, machine learning techniques can take as inputs carbon prices, energy consumption, industrial production, policy changes, and other information that are believed to affect prices. Recent research has applied neural networks to forecast prices in the Guangdong carbon market. The results indicate that the model with real-time industrial activity and regulatory announcements can explain price swings better than existing methods. Furthermore, the model can easily identify risk factors such as energy price spikes. Machine learning techniques can also help monitor risks by analyzing unstructured data such as enterprise compliance reports or market sentiment to uncover liquidity shortages. However, high-quality standardized emissions data and substantial computational infrastructure must be developed before machine learning can be widely used in carbon markets with smaller scopes. The development of data standards and training programs can help improve risk forecasting, allowing for better allowance allocations and market outcomes.

In this section, we present two methodological tools to help assess risks in carbon markets in China. Cross-disciplinary risk assessment frameworks can provide a comprehensive view of risks that are not addressed by the economics, environmental science, or social sciences approaches. Risk assessment can reveal risks that are not considered by market analysis, environmental science, or social equity evaluations, and can reveal the potential impacts of risks on ecological and social

well-being. For example, a risk assessment of carbon markets in the Beijing-Tianjin-Hebei region found that an increase in market inefficiencies could increase health costs from delayed emissions reductions. To quantify risks, the framework recommends using risk metrics such as the distribution of compliance costs among income groups. In an analysis of China's carbon markets, the distribution of compliance costs reveals the risk of excluding small and medium-sized enterprises from the carbon market, which could have large impacts on emissions, but are often limited from participating in carbon markets. Unlike analyses that focus on policies, this framework evaluates the trade-off between economic efficiency and social fairness. Challenges to using the framework include coordinating the expertise of people from different disciplines and standardizing the metrics used by researchers from different backgrounds. To remove these challenges, national interdisciplinary research networks should be developed, and standardized guidelines developed for use by researchers from different backgrounds. Fuzzy Logic for Uncertainty Management: Uncertainties in China's carbon market stem from incomplete or ambiguous data on emissions or policy impacts. Fuzzy logic is an innovative methodology to model vague or fuzzy variables. For example, it can model the probability of regulatory changes or the actual level of enterprise compliance with carbon market rules. In contrast to probabilistic simulations that require certain distributions, fuzzy logic uses flexible membership functions. An analysis of the Hubei carbon market used fuzzy logic to model liquidity risks in the carbon market. Liquidity risk refers to the risk that market participants are unable to trade as they wish because of insufficient supply or demand of carbon allowances [38]. The analysis showed that using fuzzy logic to model imprecise information about the trading activity of enterprises and the enforcement of policies led to more accurate risk profiles than using point estimates.

The framework revealed that carbon market risks in China include information disclosure risks, which stem from the lack of complete and accurate information on enterprise emissions. To help improve risk management in China's carbon markets, the framework recommends training and standardized protocols for using fuzzy logic. Lastly, based on quantitative methods, these will also promote some degree of voice sharing through dialogue by the development of dialogue channels between stakeholders. Thereby assisting in aligning priorities, creating trust, and finding prospects of mutual operations to tackle the systemic challenges of carbon market.

4. Carbon Market Risks Challenges

Regulatory uncertainty stands as one of the most significant issues hindering the progress of carbon markets. Policies governing carbon trading frequently shift, making it difficult for businesses and investors to navigate long-term strategies. Abrupt changes in emission reduction targets or allocation methods destabilize markets and deter investments in low-carbon technologies. Compounding this issue is the lack of harmonized policies across regions, which creates inefficiencies

in global carbon trading. While some areas enforce stringent carbon pricing measures, others maintain lenient emission allowances, resulting in imbalances that undermine market efficiency. Additionally, operational challenges such as outdated infrastructure and manual processes further impede market progress. Slow settlement times and inadequate monitoring systems increase costs and administrative burdens, discouraging participation. Embracing modern technologies like blockchain for secure transactions and AI-driven tools to optimize processes could address these inefficiencies, fostering a more reliable and efficient carbon market [38]. Liquidity and volatility issues significantly impact the effectiveness of carbon markets, particularly in smaller or developing regions with limited participation. Low trading volumes hinder efficient price discovery, while price volatility—caused by supply-demand imbalances, macroeconomic shocks, and abrupt policy changes—introduces uncertainty [38]. For example, sudden surges in carbon allowances can lead to sharp price drops, destabilizing markets. These challenges highlight the need for mechanisms such as market stability reserves and carbon derivatives to mitigate risks and maintain price equilibrium. Furthermore, limited awareness and participation, especially among Small and Medium Enterprises (SMEs) in developing regions, restrict market growth. Many businesses perceive carbon trading as overly complex, focusing instead on short-term financial survival rather than long-term sustainability goals. Targeted education, financial incentives, and efforts to simplify market processes are critical to increasing participation and fostering a more inclusive and productive market environment.

Fragmentation among regional carbon markets prevents the creation of a cohesive global trading system [38]. Differing rules and standards across regions, such as in China where provincial policies often misalign with national objectives, create regulatory ambiguity and limit market integration. A unified carbon pricing mechanism, such as a national cap-and-trade system or uniform carbon tax, is essential for reducing uncertainties and enabling global price harmonization. Transparency and accurate reporting of emissions data are equally vital. Current inconsistencies in data reporting and verification erode trust and accountability. Standardized frameworks and advanced digital tools for real-time monitoring can improve transparency and build confidence among stakeholders [38]. Additionally, technological limitations, including the lack of secure transaction systems and AI-based predictive analytics, hinder the sociability and performance of carbon markets. Investments in innovative technologies can address these issues, streamline operations, and ensure the long-term sustainability of carbon markets, ultimately enhancing their role in global climate change mitigation efforts.

5. Discussions

5.1. Barriers and Pathways to Strengthen China's Carbon Market

The carbon market in China has emerged as one of the cornerstones of its climate action strategy and thus an important lever to meet the global challenge of green-

house gas emissions reduction. However, several challenges must be overcome so that this market works effectively and for a long period of time. Among them are regulatory fragmentation, price volatility, data transparency deficits, and low market liquidity. Each of these factors acts in concert with the others to impact functionality and stability in the carbon market in such a way that its ultimate goals-constraining peak carbon emissions by 2030 and reducing them to carbon neutrality by 2060-become out of reach [38]. The regulatory landscape is highly fragmented across different regions and provinces in China's carbon market, causing inefficiency and obstruction to market integration. Despite that fact, regions such as Shanghai and Guangdong show leading roles; nevertheless, most small regional markets face poor infrastructures that are under-resourced, under participation, and erratic policy enforcement. These heterogeneous conditions raise systemic risks and limit scalability to the national market level. In this respect, regional policies need to be harmonized by establishing a unified and standardized regulatory framework to establish a single national market. Lessons can be learned from pilot programs that have been conducted in regions like Beijing, Shanghai, and Guangdong. These show the need for localized strategies tailored to local economic and industrial conditions. For instance, Shanghai is at a relative advantage regarding the management of liquidity, whereas Beijing has successfully connected the carbon-trading program with other relevant policy areas, such as renewable energy adoption and energy efficiency [39]. These varied local-level successes reveal the enabling role stakeholder engagement and adaptive policy design play in overcoming the specified market problems. Yet, the pilots simultaneously show that regional successes are hard to extend at a national scale.

Liquidity and price volatility are critical challenges that threaten the stability of the market and, at the same time, prevent long-term investment. Small regional markets with low trading volumes hardly attract participants to facilitate price discovery efficiently. This illiquidity not only destabilizes the market but also deters enterprises and investors who see the carbon market as volatile and untrustworthy. Moreover, abrupt policy changes and macroeconomic shocks further amplify price fluctuations, creating uncertainty for participants [39]. For the successful management of these risks, market stability reserves and carbon derivatives are some mechanisms that provide great support, but their deployment must ensure strong regulatory oversight and widespread diffusion. The technological innovation can solve many of these issues. Blockchain technology, for example, provides a secure and transparent route for tracking carbon credits to reduce the threat of falsified reporting. AI can optimize trading mechanisms, predict market trends, and build up complex decision-making processes. The IoT can also allow for real-time emissions monitoring, making reporting timely and more accurate. While these are promising developments, the adoption of these technologies remains patchy, and their scalability at the national level is far from guaranteed. It is expected that policymakers and market participants will invest in the development and deployment of these technologies to further enhance the efficiency and trans-

parency of the carbon market. In any working carbon market, engagement with the stakeholders is also another key building block. Huge compliance and operation costs are involved, which again become very discouraging factors for enterprise participation in emission trading [40]. Many companies, especially SMEs, have no resources to invest either in low-carbon technology or in dealing with the carbon credit trading complexity.

The catch, however, is that regulators also must balance stability with flexibility for innovation and ever-changing economic circumstances. Investors require transparency and predictability in decision-making again via standardized frameworks in reporting and policy implementation. A holistic approach thus needs to be an inclusive and collaborative process of long-term thinking and varied stakeholder concerns. Probably the most formidable challenge yet remains the integration of regional markets into a coherent national system. Harmonized carbon pricing must be complemented by a harmonized framework for emissions reporting and verification to build market confidence and ensure better transparency. Lessons from other international systems, like the European Union Emissions Trading System (EU ETS), may also be instructive. For instance, the Market Stability Reserve in the EU has experience in price volatility control to maintain market stability [41]. These best practices will help improve the resilience and performance of China's carbon market. The China carbon market represents an important step towards fulfilling the country's ambitious goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. However, the market is plagued by multifaceted factors that limit its effectiveness and long-term prospects, ranging from regulatory fragmentation to price volatility and deficiencies in data transparency, as well as low market liquidity. Recent innovations in risk measurement, from machine learning-enhanced copula models to network analysis to real-time data analytics, can help investors understand these dynamics and uncover new opportunities as the market develops [42].

5.2. Regulatory Fragmentation, Market Instability, and Technological Gaps

The carbon market's regulatory framework remains fragmented at a sub-national level, with individual regulatory policies of each market frequently at variance with national objectives, exposing the market to systemic risks and hampering the development of a cohesive national trading system. Advanced markets such as Shanghai and Guangdong have demonstrated best practices in liquidity management, higher trading volumes, and stakeholder engagement. The absence of these resources in smaller markets has exposed the carbon market to additional risks that come from having an under-resourced, low-participation, and ill-resourced market with respect to policy tools, such as a lack of hedging mechanisms. Recent research has highlighted that the degree of regulatory divergence between markets can explain 15% - 20% of regional variance in carbon price stability [42]. Harmonizing regional policies within a unified regulatory framework will be essential to

mitigating these risks. Recent literature suggests that a balanced, unified regulatory framework will allow for a tiered approach to regulation that draws on lessons from successful pilot programs, such as those in Beijing, Shanghai, and Guangdong, and allows for localized policies that build on regional strengths and best practices. Beijing's model for linking emissions trading with policies related to renewable energy and energy efficiency can serve as a scalable framework for carbon pricing [42]. However, tapping into these successes will require balancing resource allocation to leverage these successes with tools for risk measurement and management, such as network contagion models to identify weak market nodes in need of reinforcement, and learning from international benchmarks such as the European Union's Market Stability Reserve (EU MSR) and its demonstrated 10% reduction in price volatility through dynamic supply adjustments (Sun *et al.*, 2024). Liquidity shortages and price volatility are obstacles that impede investment in the carbon market. Both problems are particularly pronounced in smaller regional markets [42].

Recent analyses using copula models find that carbon prices exhibit strong tail dependencies with exogenous factors such as energy price shocks and macroeconomic instability, with correlation coefficients exceeding 0.7 during periods of price volatility. A recent study finds that a 30% increase in the coal price in 2024 caused a 12% decrease in carbon credit demand. To date, recent literature has argued that market stability reserves and carbon derivatives would help to contain these two problems; and both require sound predictive analytics for their effective deployment. For example, the use of advanced analytical techniques, such as GARCH with neural networks, can improve short-term price forecasting accuracy by 25%. However, the effectiveness of these models still depends on regulatory oversight and market participation. Recent literature also finds that financial incentives can spur participation of Small and Medium Enterprises, which constitute 40% of emissions but only 15% of trading activity. Technological innovation is essential for overcoming operational inefficiencies and lack of transparency. For example, blockchain technology can provide a tamper-proof way to track carbon credits and has garnered attention for its potential in reducing falsified reporting. Pilot applications of blockchain have already yielded a 18% reduction in falsified reporting in China [43]. The IoT can provide real-time monitoring of emissions, with a 22% greater accuracy compared to non-IoT methods. Recent studies have also found that AI can be used to improve trading strategies in the carbon market. However, the above technologies are still in their early stages of adoption, and technological infrastructure is lacking in many underdeveloped regions. The bigger challenge is data transparency. Inconsistent emissions reporting by companies has been eroding stakeholder trust. Advanced risk measurement tools have revealed that incomplete data explains about 30% of the market uncertainty in the China carbon trading system [43]. Standardizing reporting frameworks and integrating real-time analytics could be useful lessons for the China NERS project (Wang *et al.*, 2024).

5.3. Stakeholder Engagement and Systemic Resilience

Stakeholder dynamics make it challenging to deliver on the potential of emissions trading. They can increase the cost of compliance and reduce participation. Our research shows that compliance costs for SMEs can be as high as 8% - 12% of the operational budget (Tang *et al.*, 2023). This can make it difficult for enterprises to engage in emissions trading in the first place. Regulators face a similar dilemma. On the one hand, they want to ensure the stability of the system. On the other hand, they want to encourage innovation. Investors require a degree of certainty and transparency before they invest in a system. More than half of all investors surveyed said that they would require greater transparency before investing in a company. Recent qualitative research suggests that stakeholder dialogues can add value. They can help to bring together different expertise and reduce policy misalignments if the right collaborative platforms are in place [43]. A holistic approach to risk management includes both quantitative risk models as well as input from stakeholders. For example, combining Monte Carlo simulations with stakeholder feedback could have allowed regulators in the pilot markets to predict liquidity crises in the EU ETS with an accuracy of 85% [43]. International cooperation can also help to build systemic resilience, for example about specific aspects such as the EU ETS.

The challenges outlined above will play a decisive role in shaping the future trajectory of China's carbon market. If left unaddressed, issues such as regulatory fragmentation, price volatility, and weak market infrastructure may undermine investor confidence and hinder the market's ability to function as an effective emissions reduction tool. However, with the deployment of well-designed regulatory frameworks and advanced technical instruments, systemic risks can be effectively contained—potentially lowering the cost of capital for low-carbon projects by 5% - 7%, thereby accelerating investment in clean energy, industrial decarbonization, and green innovation. Conversely, failure to mitigate institutional fragmentation and market instability could lead to a 10% - 20% increase in the cost of achieving emissions reductions and delay progress toward China's 2030 carbon peaking goal by up to 15% [44]. To avoid these consequences, companies, investors, and other key stakeholders must proactively engage in risk management, adopt advanced measurement and forecasting tools, and draw lessons from both domestic pilot programs and international carbon market experiences. By doing so, they can collectively strengthen the resilience and credibility of the carbon market and ensure its effective contribution to China's broader low-carbon economic transition and climate governance strategy [44].

6. Conclusions

China's carbon market provides huge potential, not only for climate change mitigation but also for enabling sustainable economic development. As one of the biggest emitters in the world, it is important to have China commit to emission

reduction via a sound system of carbon trading-first and foremost, to national environmental objectives and second to global climate stability. This would, in turn, create an incentive mechanism whereby industries are moving towards cleaner technologies with lower emissions, thereby reducing the carbon economy to a low level. The realization of its full potential is fraught with major challenges: regulatory fragmentation, price volatility, data transparency, and operational inefficiencies. The unified regulatory framework is highly needed for the ultimate success of China's carbon market. Harmonization of regional policies and development of a uniform national system will cut down inefficiencies and build market confidence. Stringent regulatory oversight will ensure that enforcement is consistent and will help contain the risks of price volatility and liquidity shortages. Market stability reserves and mechanisms for carbon derivatives will add to market stability and encourage more participants. International cooperation, coordinating especially with international mechanisms like the EU Emissions Trading System, may bring new lessons and experiences that could help further improve the effectiveness and robustness of China's carbon market. Technological innovation will be one of the critical solutions to many challenges of the market. Blockchain technology could make tracking carbon credits secure and transparent, while artificial intelligence optimizes trading strategies and market trend predictions. It also enables IoT to further conduct real-time monitoring of the emissions, adding more accuracy and compliance to the data.

In this light, increased investment in advanced digital monitoring, reporting, and verification (MRV) technologies, as well as data-sharing platforms and blockchain-enabled traceability systems, will become increasingly important for both policymakers and market participants. These tools are essential for improving the operational efficiency, data accuracy, and overall transparency of China's carbon market—particularly as the system scales up and becomes more integrated with national climate strategies. Moreover, to ensure widespread and equitable market participation, especially among small and medium-sized enterprises (SMEs) that often lack sufficient financial and technical resources, a combination of targeted education programs, technical assistance, and well-structured financial incentives is urgently needed. This transformation requires coordinated and sustained collaboration between government agencies, industry leaders, financial institutions, academic researchers, and civil society organizations. Building such a multi-stakeholder governance framework will not only strengthen market inclusiveness and resilience but also enhance policy credibility and responsiveness in the face of evolving economic, technological, and environmental conditions. A well-functioning, transparent carbon market can more effectively send long-term price signals, reduce transaction costs, and stimulate low-carbon innovation across sectors. If China is able to confront and resolve its current carbon market challenges through institutional reform, policy innovation, and strategic investment, it will be well-positioned to assume global leadership in climate governance. Such success would not only support the country's own dual carbon goals—carbon peaking before

2030 and carbon neutrality before 2060—but also serve as a model for emerging economies seeking to align carbon markets with broader sustainable development agendas. In doing so, China could significantly influence the global trajectory toward a more climate-resilient, low-carbon economic future.

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Conflicts of Interest

The authors declare no conflicts of interest.

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