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# How Efficient Are China's and the EU's Carbon Markets? A Comparative Analysis Using the Adjusted Market Inefficiency Magnitude

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**Abstract:** This paper examines the time-varying efficiency levels in the European Union's and China's carbon markets, including China's pilot markets. A comparative analysis of these markets' efficiency levels is conducted using the recently developed Adjusted Market Inefficiency Magnitude (AMIM). Our findings indicate that China's national carbon market remained inefficient during its first two years of operation, lagging considerably behind the efficiency levels observed in the European Union's carbon market. Additionally, China's pilot markets have generally exhibited inefficiency, with some exceptions: Shanghai showed efficiency between 2016 and early 2020, while Tianjin and Beijing have demonstrated efficiency since mid-2020. Notably, our results provide no evidence of a substantial deterioration in the efficiency of the Chinese carbon markets during the period encompassing the COVID-19 pandemic. These findings are relevant to emission-intensive industries, policymakers, and investors engaged in carbon and energy markets. The study discusses the impact of market inefficiency on low-carbon development, providing policy recommendations to enhance the effectiveness and maturity of China's carbon markets.

**Keywords:** carbon markets; market efficiency; adaptive market hypothesis; Adjusted Market Inefficiency Magnitude; COVID-19 pandemic.

**JEL classification:** G14; G15.

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## 1. INTRODUCTION

Climate change, primarily driven by greenhouse gas (GHG) emissions, particularly carbon dioxide, has emerged as a significant global challenge. In response, the Kyoto Protocol, established under the United Nations Framework Convention on Climate Change, set binding emission targets and introduced carbon trading mechanisms to facilitate cost-effective GHG reductions. Emission Trading Schemes (ETS), adopted by both developed and developing economies, offer a flexible and economically efficient means of achieving these emission reduction targets. By enabling the trade of emission allowances, these markets ensure that abatement occurs where it is most cost-efficient, positioning them as a critical tool in global efforts to mitigate climate change (Bayer and Aklin, 2020; Cui *et al.*, 2021; Tang *et al.*, 2021).

The growth of carbon markets has been remarkable, now reaching substantial dimensions. For instance, in 2023, the European Union and China accounted for 1.1 and 5.1 billion tons of carbon dioxide emissions, respectively (European Securities and Markets Authority, 2024; Ministry of Ecology and Environment of the People's Republic of China, 2024). As carbon markets continue to expand, they play an increasingly pivotal role in international climate policy. The existence of well-functioning carbon markets has been linked in empirical literature to various beneficial outcomes. These include reductions in industrial carbon dioxide emissions (Zhang *et al.*, 2020a; Ministry of Ecology and Environment of the People's Republic of China, 2024), improved carbon emission efficiency, and lower overall emission-reduction costs (Hua *et al.*, 2011; Wu *et al.*, 2023). Carbon markets have also been shown to stimulate corporate innovation (Pan *et al.*, 2022), ultimately improving welfare, enhancing the allocation efficiency of production costs, and fostering coordinated regional development (Fan *et al.*, 2016).

For market participants, assessing how the carbon market operates is a crucial step in effectively implementing carbon management strategies, making this evaluation highly relevant for investors, risk managers, and environmental policymakers alike (Krishnamurti and Hoque, 2011). Carbon-emitting entities, for instance, are primarily concerned with paying no more than the fair value for greenhouse gas emissions hedging contracts. On the other hand, policymakers aim to ensure that carbon trading meets its objective of achieving emission reductions at the lowest possible cost. This goal can only be realized if carbon prices are aligned with fundamental factors, such as marginal abatement costs, thereby allowing polluters to rely on ETS prices when projecting future carbon costs. However, this holds true only if the market itself is efficient—meaning that prices fully incorporate all available information, preventing any investor from consistently achieving abnormal risk-adjusted returns (Fama, 1970, 1991). The realization of the benefits offered by carbon markets is therefore closely tied to their informational efficiency, which is traditionally evaluated through the lens of the Efficient Market Hypothesis (EMH) as defined by Fama (1970). The weak form of EMH suggests that past information cannot predict future returns, implying that markets follow a random walk. However, subsequent research has highlighted that actual financial markets may exhibit complex and nonlinear dynamics, with returns often displaying leptokurtic distributions that deviate from the normality assumption commonly adopted in conventional financial models (Chu *et al.*, 2019; Okorie and Lin, 2021; Lobão and Costa, 2023). These empirical regularities suggest that market behavior may be more complex than that captured by standard models used to assess market efficiency.

In response to the limitations of the EMH, researchers have increasingly argued that market efficiency is not binary, but rather should be measured in degrees (Campbell *et al.*, 1997). Lo (2004) introduced the notion that market efficiency is not static, but fluctuates over time, adapting to changing market conditions. This led to the development of the Adaptive Market Hypothesis (AMH), which incorporates principles of competition, adaptation, and natural selection. Unlike EMH, AMH suggests that market efficiency evolves dynamically, alternating between predictable and non-predictable returns. This perspective has shifted the focus towards understanding the time-varying nature of market efficiency. Recent evidence, as presented by Chu *et al.* (2019), Okorie and Lin (2021), and Lobão and Costa (2023), among others, often challenges the more rigid assumptions of EMH, demonstrating that markets exhibit phases of adaptation and change.

Drawing on the AMH, this article examines the evolution of market efficiency in carbon emission trading schemes in the European Union and China using the Adjusted Market Efficiency Magnitude recently proposed by Tran and Leirvik (2019). For China, our sample includes both the national carbon market and the regional pilot markets (Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, and Tianjin), with the sample period extending from the initial trading day of each market through September 28, 2023. The Adjusted Market Efficiency Magnitude not only allows us to test whether these markets were efficient or inefficient during specific periods, but also enables us to quantify the degree of efficiency over time and compare the relative efficiency of different markets.

The differences in market efficiency between the EU and Chinese carbon markets may be related to their substantially different levels of market maturity, liquidity, regulatory development, and investor composition. The EU ETS is a more mature market with a longer trading history and a broader and more established participant base, whereas China's national ETS is relatively young and operates within a more recent and rapidly evolving institutional framework. These differences may affect the speed with which information is incorporated into prices and the ability of market participants to arbitrage predictable price patterns. Moreover, differences in investor composition and trading experience may contribute to heterogeneous responses to new information and to the persistence of behavioral biases. In line with the AMH, these institutional and market characteristics suggest that efficiency may differ across markets and evolve as participants adapt to changing market conditions.

Based on these arguments, we formulate the following hypotheses. First, given the substantially greater maturity and liquidity of the EU ETS, we expect the EU carbon market to exhibit higher levels of informational efficiency than China's national carbon market during the latter's initial years of operation:

***H1****: The EU ETS exhibits higher informational efficiency than China's national ETS during the early development of the Chinese national market.*

Second, the Chinese pilot markets differ considerably in terms of market maturity, liquidity, regulatory arrangements, and participant composition. We therefore expect these differences to be reflected in heterogeneous levels of informational efficiency across the pilot markets:

***H2****: Informational efficiency differs across China's regional pilot carbon markets, consistent with differences in market development, institutional conditions, liquidity, and participant characteristics.*

Finally, the AMH implies that market efficiency should not be regarded as a constant characteristic but as a time-varying outcome of changing market conditions and participant adaptation. Accordingly, we expect efficiency in both the EU and Chinese carbon markets to fluctuate over time rather than remain persistently at a single level:

***H3****: Informational efficiency in carbon markets is time-varying, with periods of increasing and decreasing efficiency occurring as market conditions and participants' behavior evolve.*

Our findings reveal that China's national carbon market remained inefficient throughout its first two years of operation, markedly trailing the efficiency of the European Union's carbon market. Furthermore, China's pilot markets have generally exhibited inefficiency, with certain exceptions: Shanghai demonstrated efficiency between 2016 and early 2020, and Tianjin and Beijing have shown efficiency since mid-2020. Importantly, our results provide no evidence of a substantial deterioration in the efficiency of the Chinese carbon markets during the COVID-19 pandemic.

Our study makes several key contributions. First, to the best of our knowledge, it is the first to examine the informational efficiency of China's national carbon market, launched in July 2021, and to compare it with the efficiency of the European Union's carbon market. This analysis is particularly significant given that the carbon markets in these two economic regions are by far the largest globally in terms of the amount of greenhouse gas emissions they cover.

Second, we are the first to use the Adjusted Market Efficiency Magnitude to examine the efficiency of carbon markets. This measure offers a significant advantage over other efficiency metrics: it is designed in line with the principles of the AMH, enabling quantification of a market's efficiency over time and determining whether it is efficient or inefficient. Additionally, AMIM provides a continuous, direct measure of efficiency that is robust to varying data frequencies, making it particularly well-suited for analyzing low-liquidity markets, such as carbon markets (Tran and Leirvik, 2019, 2020). In this respect, our methodological approach goes beyond many existing studies (e.g., Zhao *et al.*, 2017; Zhou *et al.*, 2019), which assess carbon market efficiency through a static lens without examining how efficiency evolves over time.

Third, our methodology facilitates direct comparisons between the efficiency levels of the carbon markets in China and the European Union. This distinguishes our work from previous research, which often focuses on the efficiency of carbon markets within a single country or economic region (e.g., Liu *et al.*, 2021; Sattarhoff and Gronwald, 2022; Zhong *et al.*, 2023). Such cross-market comparisons are particularly valuable in the context of emerging carbon markets, as they help identify best practices in more efficient markets that can be replicated in less efficient ones.

Finally, by using a more recent dataset, we extend the analysis of market efficiency to a period that includes the COVID-19 pandemic, a major episode of financial and economic

disruption that has received comparatively limited attention in the carbon-market efficiency literature.

The remainder of the article is organized as follows. Section 2 provides an overview of the institutional background of the EU and Chinese carbon markets, highlighting differences in market maturity, regulatory frameworks, market participation, liquidity, and market design. Section 3 reviews the literature on efficiency in carbon markets. Section 4 introduces the data and methodology employed in the empirical study. Section 5 discusses the results obtained from our empirical analysis. Finally, Section 6 concludes the article by summarizing the key findings, providing policy recommendations, and offering suggestions for future research.

## 2. INSTITUTIONAL BACKGROUND

The EU and Chinese carbon markets share the objective of reducing greenhouse gas emissions through market-based mechanisms, but they differ substantially in market maturity, institutional design, participant structure, and trading conditions. These differences provide important context for interpreting the informational efficiency patterns examined in this study. In particular, market maturity, liquidity, participation, and regulatory arrangements may affect market participants' ability to process information and to arbitrage predictable price patterns. The following discussion, therefore, focuses on the institutional characteristics most relevant to the comparison between the EU ETS, China's national ETS, and the Chinese regional pilot markets.

### 2.1. The European Union Emissions Trading System

The European Union Emissions Trading System (EU ETS) was established in 2005 and is currently operating under its fourth trading phase (2021–2030). Its institutional framework is based on a common EU-wide regulatory architecture established by the EU ETS Directive and progressively strengthened through successive reforms. The system covers power generation and energy-intensive industries, as well as aviation and, since 2024, maritime transport (European Commission, 2025).

The EU ETS has developed into a relatively mature carbon market, supported by a long trading history, a broad compliance base, and sophisticated trading infrastructure. Allowances are allocated through a combination of auctioning and free allocation, while secondary-market activity includes spot transactions, futures, options, and over-the-counter trading. Financial intermediaries, investment firms, credit institutions, and investment funds play an important role alongside regulated entities. These characteristics provide market participants with considerable experience and opportunities for information acquisition, risk management, and arbitrage. Consequently, the relatively high degree of market maturity and liquidity of the EU ETS may facilitate price discovery and the incorporation of information into allowance prices. This does not imply that the EU ETS is consistently efficient, since its prices remain sensitive to regulatory changes, energy market conditions, macroeconomic developments, and changes in allowance supply. Rather, its institutional development provides an environment in which deviations from informational efficiency may be arbitraged away more rapidly.

### 2.2. China's National Emissions Trading System

China's national emissions trading system was launched on 16 July 2021, following the experience accumulated through regional pilot markets. The national system initially focused on the power-generation sector and included 2,162 key emitting entities, covering approximately 4.5 billion tonnes of $CO_2$ emissions (Li *et al.*, 2022).

The national ETS was therefore considerably younger and less financially developed than the EU ETS during the period examined in this study. Its initial participant base was concentrated primarily among regulated power-generation companies, while financial participation and the development of a broader secondary market remained comparatively limited. In addition, the initial system relied predominantly on free allocation based on benchmarks and adopted an emissions-intensity-based approach rather than an absolute emissions cap comparable to that of the EU ETS (Li *et al.*, 2022).

The combination of limited trading experience, a relatively concentrated participant base, and a developing market infrastructure may affect information aggregation and price discovery. A younger market may require time for participants to learn to interpret carbon price information, develop trading strategies, and respond to predictable price movements. These characteristics, therefore, provide a plausible institutional context for the lower informational efficiency observed in China's national ETS during its initial years.

### 2.3. China's Regional Pilot Emissions Trading Systems

Before the national ETS was established, China introduced regional pilot markets in Beijing, Shanghai, Guangdong, Tianjin, Hubei, Chongqing, Shenzhen, and subsequently Fujian. These markets provided the institutional and practical experience underlying the development of the national system, but they were characterized by substantial heterogeneity in market design and development.

The pilots differed in sectoral coverage, inclusion thresholds, allowance allocation, compliance rules, participant numbers, and trading activity. Zhang (2015) document considerable variation in sectoral coverage across the pilot markets, while Liu and Zhang (2019) show substantial differences in market maturity. Liquidity was also highly heterogeneous. Chang *et al.* (2018) find that Hubei, Guangdong, and Shenzhen generally exhibited greater liquidity than Beijing, Shanghai, Tianjin, Chongqing, and Fujian, and argue that market fragmentation, insufficient transactions, and limited transparency can constrain pricing efficiency.

Such heterogeneity is particularly relevant to the present study because it implies that China's pilot markets should not be treated as a single homogeneous market. Differences in institutional development, liquidity, participation, and trading experience may generate different incentives and opportunities for information acquisition and arbitrage. The regional pilots, therefore, provide a useful setting for examining whether informational efficiency varies across markets operating under different institutional conditions.

### 2.4. Institutional Differences and Informational Efficiency

Table 1 summarizes the principal institutional differences between the markets examined in this study. The EU ETS combines a long trading history, a broad participant base, developed secondary and derivatives markets, and a relatively integrated regulatory framework. China's national ETS, in contrast, was still in an early stage of institutional and market development during the sample period. The Chinese pilots occupy an intermediate and heterogeneous position, with substantial differences in maturity, liquidity, participation, and market design.

These differences may help explain the efficiency patterns documented in the empirical analysis. Greater market maturity and liquidity can provide more opportunities for participants to learn, trade, and arbitrage predictable price patterns, whereas thin trading, limited participation, or institutional fragmentation may allow such patterns to persist. Nevertheless, these mechanisms should be interpreted as plausible contextual explanations rather than causal determinants, since the empirical framework employed in this study does not separately identify the effects of individual institutional characteristics on AMIM.

**Table 1. Institutional characteristics of the EU and Chinese carbon markets**

| Characteristic | EU ETS | China's national ETS | Chinese pilot ETSs | Potential relevance for efficiency |
|---|---|---|---|---|
| Establishment | 2005 | 2021 | 2013–2014; Fujian in 2016 | Longer experience may facilitate learning and price discovery |
| Market maturity | Relatively high | Relatively low during the sample period | Heterogeneous | Experience may affect information processing and adaptation |
| Regulatory structure | Common EU-wide framework | National framework | Greater regional discretion | Institutional fragmentation may affect information diffusion |
| Sectoral coverage | Broad and expanding | Initially focused on power generation | Substantially heterogeneous | Broader coverage may increase participant diversity |
| Participant structure | Compliance entities and substantial financial participation | Initially concentrated on regulated power entities | Heterogeneous across regions | Greater diversity may enhance information aggregation |
| Liquidity and trading activity | Relatively high and developed | Developing | Highly heterogeneous | Greater liquidity may facilitate arbitrage and price discovery |
| Secondary markets | Spot, futures, options and OTC markets | Initially dominated by spot trading | Primarily regional spot markets | Developed markets provide additional opportunities for information incorporation |
| Market integration | EU-wide market | National market | Fragmented regional markets | Fragmentation may constrain liquidity and information diffusion |
| Overall institutional environment | Mature and relatively integrated | Young and developing | Diverse levels of development | Provides context for cross-market and time-varying efficiency differences |

*Sources: Zhang (2015); Chang et al. (2018); Liu and Zhang (2019), Li et al. (2022), European Securities and Markets Authority (2024), European Commission (2025).*

## 3. LITERATURE REVIEW

Over time, numerous studies have examined the efficiency of carbon markets. Table 2 summarizes the key features of these studies.

**Table 2. Summary of literature on carbon market efficiency**

| Study | Markets under analysis | Sample period | Methodology | Main results |
|---|---|---|---|---|
| Montagnoli and de Vries (2010) | EU ETS (Phase I and Phase II) | June 2005 – December 2009 | Variance ratio test | Phase I was characterized by inefficiency, while Phase II showed improvements towards market efficiency |
| Joyeux and Milunovich (2010) | EU ETS (Phase I) | June 2005 – December 2007 | Cost-of-carry hypothesis | The market exhibited inefficiency throughout the entire data sample, although there were signs of improvement over time |
| Daskalakis (2013) | EU ETS (Phase II) | January 2008 – December 2011 | Technical analysis rules | From 2010 onwards, the results indicated consistency with weak-form market efficiency |
| Charles *et al.* (2013) | EU ETS (Phase II) | March 2009 – January 2012 | Cost-of-carry hypothesis | The market demonstrated inefficiency across the entire sample period |
| Zhao *et al.* (2017) | China's ETS pilots | June 2013 – September 2015 | Unit root test, run test | Beijing was the only market to exhibit efficiency throughout the entire sample period. Tianjin, Shanghai, and Shenzhen were inefficient during the initial period but became efficient in later phases. |
| Wang and Wu (2018) | China's ETS pilots | June 2013 – January 2015 | Variance ratio test | Only the Hubei market displayed weak-form efficiency |
| Fan *et al.* (2019) | China's ETS pilots | June 2013 – February 2018 | Multifractal detrended fluctuation model | While most markets remained inefficient, there were indications of improvement over time, except for the Tianjin market. |
| Zhou *et al.* (2019) | China's ETS pilots | June 2013 – May 2018 | Variance ratio test | The majority of markets were inefficient, with only Beijing, Hubei, and Fujian demonstrating efficiency |
| Liu *et al.* (2020) | China's ETS pilots | June 2013 – August 2019 | Variance ratio test, multifractal detrended fluctuation model | According to both methods used, only Guangdong and Hubei exhibited weak-form efficiency, though the overall level of efficiency remained low |
| Zhang *et al.* (2020b) | China's ETS pilots | June 2013 – December 2019 | Variance ratio test | In general, markets were inefficient, though the Hubei market was on the verge of reaching efficiency |
| Chen *et al.* (2021) | Hubei's ETS pilot | April 2014 – August 2020 | Variance ratio test | The market consistently exhibited weak-form efficiency throughout the entire sample period |
| Wu and Qin (2021) | China's ETS pilots | January 2017 – June 2019 | GARCH(1,1)-M with Kalman filter model | The Shenzhen pilot market was the most efficient, followed by Beijing, Shanghai, Guangdong, and Hubei |
| Liu *et al.* (2021) | China's ETS pilots | June 2014 – June 2019 | Fuzzy entropy method | Hubei was identified as the most efficient market, followed by Guangdong, Beijing, Shanghai, Shenzhen, Chongqing, and Tianjin |
| Sattarhoff and Gronwald (2022) | EU ETS (Phase II and Phase III) | January 2008 – February 2019 | Multifractal random walk model | The degree of efficiency in the market remained stable over the period of analysis |
| Zhong *et al.* (2023) | EU ETS (Phase III) | January 2015 – September 2022 | Structural vector autoregression stochastic volatility method | Market efficiency fluctuated significantly over the sample period. Efficiency increased in 2017 and 2018, declined around 2019, but then improved again in 2020 and 2021. However, the onset of the COVID-19 pandemic caused a decline in market efficiency |
| Venugopal *et al.* (2025) | EU ETS (Phases II, III and IV) | January 2010 – June 2024 | Multifractal detrended fluctuation model | The efficiency of the EU ETS improved steadily over the sample period, providing support for the Adaptive Market Hypothesis. |

Regarding the European Union ETS, research indicates that Phase I (2005-2007) was generally characterized by market inefficiency (Montagnoli and de Vries, 2010; Joyeux and Milunovich, 2010). During Phase II (2008-2012), market efficiency appears to have improved (Montagnoli and de Vries, 2010;

Daskalakis, 2013), though some authors have not observed these improvements (Charles *et al.*, 2013; Sattarhoff and Gronwald, 2022). In Phase III (2013-2020), significant

fluctuations in EU ETS efficiency were observed, with the COVID-19 pandemic exerting a negative impact on market efficiency (Zhong *et al.*, 2023). More recently, Venugopal *et al.* (2025), using data from January 2010 to June 2024, find that EU ETS efficiency improved steadily over time, providing support for the Adaptive Market Hypothesis.

As far as could be determined from the literature review conducted, no academic studies have yet addressed the efficiency of China's national carbon market. Regarding the country's pilot markets, the evidence suggests that they are, in most cases, informationally inefficient (Wang and Wu, 2018; Fan *et al.*, 2019; Zhou *et al.*, 2019; Liu *et al.*, 2020), although some signs of improvement in efficiency have been noted in certain markets (Zhao *et al.*, 2017; Fan *et al.*, 2019). Studies provide inconsistent findings on identifying the most efficient pilot markets in China. Some authors highlight the Hubei market as highly efficient (Wang and Wu, 2018; Zhou *et al.*, 2019; Liu *et al.*, 2020), while others identify Beijing as the most efficient market (Zhao *et al.*, 2017). Additionally, markets such as Fujian (Zhou *et al.*, 2019), Guangdong (Liu *et al.*, 2020), and Shenzhen (Wu and Qin, 2021) have been recognized for their informational efficiency. The inconsistent findings in the literature, for instance, regarding the efficiency of the EU ETS in Phase II (Daskalakis, 2013; Charles *et al.*, 2013) and the efficiency of China's pilot markets (Zhao *et al.*, 2017; Wu and Qin, 2021), may stem from studies treating efficiency as a binary concept (efficient vs. inefficient) and overlooking its dynamic nature (Zhong *et al.*, 2023). It is also noteworthy that studies in this field tend to focus on markets within a single country or economic zone, without making comparisons between markets across different countries or economic regions. The methodology employed in the present study addresses these limitations found in existing research.

## 4. METHODOLOGY AND DATA

### 4.1. Methodology

The Adjusted Market Inefficiency Magnitude, developed by Tran and Leirvik (2019), introduces an innovative approach to assessing market efficiency by capturing its time-varying characteristics and providing a continuous measure of the significance of inefficiency over time. According to the Efficient Market Hypothesis (EMH), prices should fully incorporate all available information, making returns unpredictable (Fama, 1970). To calculate the *AMIM*, we begin by modeling the carbon market returns as follows:

$$r_t = \alpha + \beta_1 r_{t-1} + \cdots + \beta_q r_{t-q} + \varepsilon_t \quad (1)$$

In the autoregressive AR(q) model of Eq. (1), significant deviations of the return coefficients from zero imply a violation of the EMH. Thus, under market efficiency, the coefficients $(\beta_1, \beta_2, \ldots, \beta_q)$ should be close to zero or statistically insignificant. The appropriate number of lags is selected based on the Akaike information criterion. AMIM is computed by first normalizing the autocorrelation coefficients in Eq. (1), which helps mitigate distortions due to variations in standard errors and correlations. The initial measure, Market Inefficiency Magnitude (MIM) in Eq. (2) is derived by summing the absolute standardized coefficients from the AR(q) model and scaling this sum against itself plus one:

$$MIM_t = \frac{\sum_{j=1}^{q} \left|\hat{\beta}_{j,t}^{standard}\right|}{1 + \sum_{j=1}^{q} \left|\hat{\beta}_{j,t}^{standard}\right|} \quad (2)$$

The *MIM* value ranges from 0 (indicating efficiency) to nearly 1 (indicating inefficiency). However, *MIM*'s reliance on lag selection can lead to overestimation (Tran and Leirvik, 2019). To address this, the *AMIM* in Eq. (3) adjusts *MIM* by subtracting a confidence interval range ($R_{CI}$), normalized to ensure the value remains between 0 and 1. The $R_{CI}$ represents the confidence interval range for *MIM* under the null hypothesis of market efficiency:

$$AMIM_t = \frac{MIM_t - R_{CI}}{1 - R_{CI}} \quad (3)$$

For detailed explanations and derivations, readers should consult Tran and Leirvik (2019). Since MIM values are bounded between zero and one, $R_{CI}$ is less than 1, ensuring continuity for both MIM and AMIM. Equation (3) guarantees that AMIM cannot exceed 1; however, it can be 0 or negative. A positive AMIM ($AMIM_t > 0$) signals market inefficiency, while an AMIM of zero or less ($AMIM_t \leq 0$) denotes efficiency in carbon trading markets. This model is robust against insignificant autocorrelation and facilitates standardized comparisons across different markets and time periods.

### 4.2. Data

Our sample data spans from the initial trading day of each market through September 28, 2023. Two primary sources provided the data used in this study. Data for the Chinese Pilot Markets (Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, and Tianjin) from their inception until December 2021 was obtained from a professional carbon market information platform (http://k.tanjiaoyi.com). Data for the EU Emissions Trading System (EU ETS), the China National Emission Trading Scheme, and for the Chinese Pilot Markets from January 2022 to September 28, 2023, was retrieved from the International Carbon Action Partnership website (https://icapcarbonaction.com/en/ets-prices). The daily continuously compounded return for day *t*, denoted $r_t$ is calculated as $r_t = \log(P_t) - \log(P_{t-1})$, where $P_t$ represents the daily closing price on day *t*.

Table 3 presents the descriptive statistics of carbon returns. This study comprises 541 observations for the China National ETS; 1,486 observations for Fujian; approximately 2,500 observations each for Beijing, Chongqing, Guangdong, Hubei, Shanghai, Shenzhen, and Tianjin; and 4,699 observations for the EU ETS.

**Table 3. Descriptive statistics of carbon returns**

| Market | # Obs. | Mean | Median | Std. Dev. | Skewness | Kurtosis | ADF | JB |
|---|---|---|---|---|---|---|---|---|
| EU | 4699 | 0.00018 | 0.00000 | 0.05043 | 0.63246 | 6.55189 | -12.954*** | 7411.205*** |
| China | 541 | 0.00031 | 0.00000 | 0.00826 | 0.25794 | 7.48724 | -7.041*** | 392.841*** |
| Beijing | 2360 | 0.00022 | 0.00000 | 0.03645 | -0.22406 | 3.76331 | -19:681*** | 439.562*** |
| Chongqing | 2220 | 0.00003 | 0.00000 | 0.04855 | -0.27660 | 13.88447 | -16.229*** | 1716.023*** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Fujian | 1486 | 0.00002 | 0.00000 | 0.03133 | 0.45209 | 5.03952 | -10.692*** | 380.994*** |
| Guangdong | 2403 | 0.00002 | 0.00018 | 0.02156 | -0.07185 | 16.40041 | -17.673*** | 3829.666*** |
| Hubei | 2328 | 0.00013 | -0.00008 | 0.01781 | 0.04941 | 20.21458 | -18.481*** | 5242.226*** |
| Shanghai | 2514 | 0.00023 | 0.00000 | 0.02495 | 0.61933 | 13.55835 | -5.557*** | 2146.327*** |
| Shenzhen | 2513 | 0.00015 | 0.00000 | 0.10638 | -0.08059 | 18.03722 | -12.256*** | 4546.125*** |
| Tianjin | 2253 | 0.00005 | 0.00000 | 0.01395 | -0.08098 | 3.89519 | -20.584*** | 337.392*** |

Notes: ADF represents the test statistic from the Augmented Dickey-Fuller unit root test, selected based on the minimum Akaike Information Criterion. JB denotes the test statistic from the Jarque-Bera normality test. *** indicates rejection at the 1% significance level.

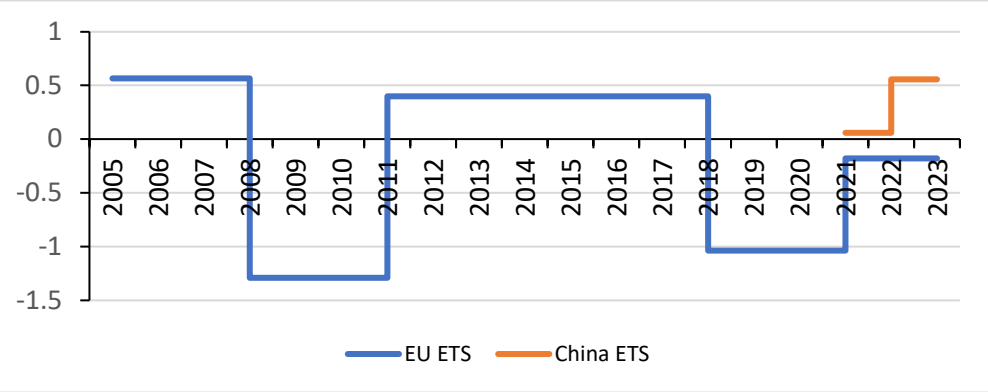
The data indicate that all markets in the sample recorded positive average returns. The highest returns were observed in China's national carbon market (with an average daily return of 0.031%), while the lowest returns were recorded in the Fujian and Guangdong pilot markets (with an average daily return of 0.002%). In the European Union carbon market, the average daily return was 0.018%. Shenzhen exhibited the highest market volatility, whereas the lowest volatility was observed in China's national market. Table 3 also highlights the skewed characteristics of the return distributions. The kurtosis values suggest that all analyzed series exhibit leptokurtic distributions, indicating heavy tails. The Augmented Dickey-Fuller (ADF) test results show that each return series is stationary at a 1% significance level, while the Jarque-Bera test statistics confirm significant deviations from normality, also at a 1% significance level.

Tran and Leirvik (2019) recommend applying the AMIM to non-overlapping 1-year windows in their sample of mature markets, including U.S. and Japanese stock portfolios. There are strong reasons to believe, however, that the data in our sample undergo more frequent shifts in internal structure and external market conditions than those observed by Tran and Leirvik (2019). This is particularly likely in China, where top-down governance plays a pivotal role in managing environmental challenges with substantial uncertainty. For example, research highlights that China's government is one of the primary drivers of pollution control efficiency (Wang *et al.*, 2021), actively promoting electric vehicle adoption (Qiu *et al.*, 2019), and supporting the development of the wind power industry (Jiang and Shi, 2023). Given this context, we opted in our study to apply the Bai-Perron (1998, 2003) structural break test so that the length of the periods used to calculate AMIM would be determined endogenously, based on the statistical characteristics of the data under analysis. However, as a robustness check, we also calculated the *AMIM* using non-overlapping windows of 252 trading days (i.e., approximately one year), in line with the recommendation by Tran and Leirvik (2019).

## 5. EMPIRICAL RESULTS

Figure 1 illustrates the evolution of efficiency in the carbon markets of the European Union and China as measured by the AMIM.

**Figure 1. AMIM for the EU ETS and China ETS**




With a positive AMIM indicating market inefficiency and values at or below zero suggesting efficiency, the EU ETS has experienced multiple phases of inefficiency and efficiency since its inception in 2005. In its first three years, this market was inefficient, transitioning to an efficient state from early 2008 until mid-2011. From that point onward, the EU ETS returned to inefficiency, remaining so until early 2018. Since then, the market has operated efficiently, though its efficiency level has shown a decline beginning at the end of 2021. Regarding the China ETS, results indicate persistent inefficiency since its launch in July 2021, with the degree of inefficiency intensifying from December 2022 onward. It is noteworthy, however, that the efficiency levels displayed by China's market in its initial years are comparable to those observed in the early period of the EU market.

The higher informational efficiency of the EU ETS relative to China's national ETS is consistent with H1 and can be interpreted in light of differences in market maturity, liquidity, institutional development, and investor experience. The EU ETS has been operating since 2005 and has therefore provided market participants with substantially more time to acquire experience in carbon-price formation, develop trading strategies, and incorporate publicly available information into prices. Its longer history has also been accompanied by successive regulatory reforms and the progressive development of market infrastructure, which may have strengthened price discovery and increased the capacity of participants to respond to new information. In contrast, China's national ETS was established only in July 2021 and initially operated within a relatively young institutional and trading environment. The limited trading history may have constrained participants' ability to learn from past market conditions and to develop stable expectations about allowance prices. Differences in market liquidity and participant characteristics may reinforce these effects, as greater trading activity and a broader and more experienced participant base can facilitate information aggregation and arbitrage. These arguments are consistent with the AMH, according to which market efficiency depends partly on the ability of market participants to adapt to the prevailing market environment.

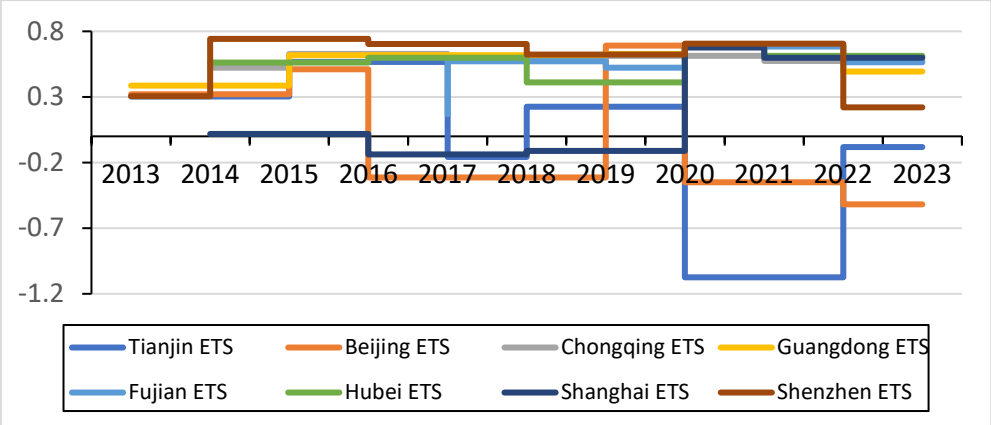
The lower informational efficiency observed in China's national carbon market is also consistent with evidence suggesting that investors in Asian markets may face greater challenges in reaching consensus on prices than their European counterparts (Zhu *et al.*, 2023). Importantly, however, the comparison should not be interpreted as evidence that the

institutional design of the Chinese market is intrinsically less efficient. Rather, the result is consistent with the possibility that a younger market requires time for participants, institutions, and trading practices to adapt and for liquidity and information-processing mechanisms to develop.

Our findings are broadly consistent with the Adaptive Market Hypothesis, particularly in relation to its prediction that markets alternate between phases of efficiency and inefficiency over time. For instance, regarding the efficiency of the EU carbon market, our results suggest that the market was inefficient during Phase I (2005-2007), with efficiency levels improving in Phase II (2008-2012). These results align with the evidence presented by Montagnoli and de Vries (2010) and Joyeux and Milunovich (2010). However, consistent with the AMH, our results do not support the notion that the market has remained generally efficient since 2010, as suggested by Daskalakis (2013), nor do they provide evidence of a consistently upward trend in efficiency over time. In fact, in Phase III (2013-2020), the market experienced an extended period of inefficiency, and since 2021, the EU carbon market has exhibited lower efficiency than in the preceding period. The substantial fluctuations in efficiency levels, including in recent periods, are consistent with findings reported by Zhong *et al.* (2023).

Figure 2 presents the AMIM trends for China's pilot carbon markets, indicating that most markets remained in the inefficiency zone throughout the analysis period. Notable exceptions, however, include the Shanghai market, which showed efficiency over a relatively extended period from April 2016 to early 2020.

**Figure 2. AMIM for China's pilot carbon markets**




Among the eight pilot markets analyzed, Tianjin and Beijing exhibit the most consistent efficiency. In the case of the Tianjin ETS, the shift to efficiency occurred in March 2017 and lasted until August 2018. Since May 2020, this market has largely maintained efficiency, albeit with variations from very high levels until early 2022, followed by a more modest efficiency level thereafter. Beijing's ETS was efficient from mid-2016 to early 2019, experienced a period of inefficiency until mid-2020, and has shown efficiency since then,

with some fluctuations. Notably, by early 2022, the Beijing market recorded the highest efficiency levels among the pilot markets, surpassing even the efficiency levels observed in the EU carbon market during this period.

The relatively stronger performance of the Beijing and Tianjin ETSs is consistent with H2 and may partly reflect differences in the institutional and economic environments in which these pilot markets developed. Beijing is an important political, administrative, and service-sector center, while Tianjin is a major industrial and logistics hub. The concentration of economic activity, market participants, and institutional expertise in these regions may have facilitated the development of carbon-market knowledge and improved the incorporation of information into allowance prices (Zhao *et al.*, 2017; Wu and Qin, 2021). In addition, both markets had several years of operation before the launch of China's national ETS, providing participants with opportunities to learn and adapt to carbon trading. The experience accumulated during the pilot phase may therefore have contributed to more effective price discovery.

The relatively high efficiency of Beijing and Tianjin should nevertheless not be interpreted as evidence that market maturity alone determines efficiency. The results for the other pilot markets indicate substantial heterogeneity, suggesting that differences in regulatory implementation, market participation, liquidity, trading activity, and investor behavior may also matter. For example, the persistence of inefficiency in several pilot markets despite their relatively long trading histories indicates that experience with carbon trading does not automatically translate into informational efficiency. Instead, consistent with the AMH, market efficiency appears to emerge from the interaction among market conditions, institutional arrangements, and participants' ability to adapt their behavior over time.

Overall, the substantial fluctuations in efficiency across the markets provide direct support for H3 and are consistent with the central prediction of the Adaptive Market Hypothesis. Efficiency does not appear to be a fixed characteristic of either the EU or Chinese carbon markets. Instead, markets move between periods of greater and lower informational efficiency as participants learn, competition changes, institutional arrangements evolve, and new information or shocks alter the market environment. The fact that the same market can exhibit prolonged periods of efficiency followed by periods of inefficiency is particularly relevant to the AMH framework. It also helps explain why previous studies of Chinese pilot markets have reached divergent conclusions: studies based on different sample periods may capture different stages of the adaptive process. The evidence, therefore, suggests that differences across markets and changes within individual markets should be considered jointly when assessing informational efficiency in carbon markets.

Finally, the evolution of market efficiency around the COVID-19 pandemic provides an opportunity to examine whether a major common shock was associated with different efficiency dynamics across the EU and Chinese carbon markets. The EU market experienced a decline in efficiency beginning in 2021, although it remained within the efficiency zone, whereas the Chinese markets did not display a comparable deterioration. In particular, both the Tianjin and Beijing ETSs achieved efficiency from 2020 onward. These results suggest that the pandemic was not associated with a uniform deterioration in carbon-market efficiency and that the response of informational efficiency to a common shock may depend on market-specific institutional and developmental conditions.

One possible explanation for the different patterns is the substantially different stage of development of the two markets when the pandemic emerged. The EU ETS was already a

mature and highly integrated market, with allowance prices reflecting expectations concerning industrial activity, energy markets, regulatory responses, and future emissions. The pandemic generated considerable uncertainty about economic activity, energy demand, production, and climate-policy responses, potentially increasing disagreement among market participants and temporarily affecting the speed with which information was incorporated into prices. By contrast, China's pilot markets were still undergoing institutional and behavioral adaptation during the pandemic. In markets such as Beijing and Tianjin, the improvement in efficiency observed from 2020 onward may therefore reflect continuing learning and adaptation among participants, which could have offset or outweighed the effects of pandemic-related uncertainty.

The absence of a pronounced deterioration in Chinese market efficiency should, however, be interpreted cautiously. The present analysis identifies changes in the AMIM around the pandemic period but does not provide a formal causal test of the effect of COVID-19. Therefore, the results should be interpreted as indicating no evidence of a substantial pandemic-related deterioration in informational efficiency in the Chinese markets, rather than as evidence that COVID-19 had no effect. More generally, this finding is consistent with the AMH view that the effect of a common shock on market efficiency depends on the prevailing competitive, institutional, and behavioral environment.

The robustness test, which involves calculating the AMIM using non-overlapping windows of 252 trading sessions, as recommended by Tran and Leirvik (2019), supports the conclusions drawn from Figures 1 and 2. The EU carbon market exhibited an efficient average level (mean ($\mu$) = –0.328, standard deviation ($\sigma$) = 0.589), in contrast to China's national carbon market ($\mu$ = 0.297; $\sigma$ = 0.335). Among China's pilot markets, Tianjin ($\mu$ = –0.148, $\sigma$ = 0.680), Shanghai ($\mu$ = –0.049, $\sigma$ = 0.653), and Beijing ($\mu$ = 0.074, $\sigma$ = 0.428) recorded the most favorable efficiency values. Conversely, the Shenzhen ($\mu$ = 0.423, $\sigma$ = 0.630) and Fujian ($\mu$ = 0.407, $\sigma$ = 0.292) markets showed the highest average levels of inefficiency during the period under analysis.

Our findings indicate that the Chinese pilot carbon markets were largely informationally inefficient, providing further support for H2 while also highlighting substantial heterogeneity across markets. This heterogeneity suggests that the existence of a common national policy framework does not imply a common level of informational efficiency. Investor behavior appears to be one potentially relevant mechanism. Recent studies have documented herding behavior among investors in these markets (Zhou *et al.*, 2022a), as well as susceptibility to cognitive biases such as overconfidence (Zhou *et al.*, 2022b), the representativeness heuristic, and non-fundamental factors such as market sentiment (Zhou *et al.*, 2023). Such behavioral patterns may slow the incorporation of information into prices and help explain the persistence of inefficiency in several pilot markets.

At the same time, our results appear to support the conclusions of authors such as Zhao *et al.* (2017) and Wu and Qin (2021), who identify the Beijing, Tianjin, and Shanghai markets as exhibiting the highest levels of informational efficiency using alternative empirical strategies. In contrast, our findings challenge the results reported by authors like Wang and Wu (2018), Zhou *et al.* (2019), Zhang *et al.* (2020b), Chen *et al.* (2021), and Liu *et al.* (2021), who have found evidence of efficiency in the Hubei market. These divergent findings may be attributed to differences in sample periods and efficiency measurement techniques and, importantly, to the fact that most studies in the literature do not account for the dynamic nature of efficiency in carbon markets.

## 6. CONCLUSION AND POLICY IMPLICATIONS

Emission trading schemes employ a market-driven approach to regulate greenhouse gas emissions and promote the economy's shift towards greener, low-carbon practices. In theory, these markets create incentives for environmentally sustainable resource allocation, ensuring that emission reduction targets are met and that the costs of emission abatement are minimized across sectors. However, effective carbon trading depends on accurate price signals, as carbon prices must be reliable and informative for high-emission firms, risk managers, and other carbon market participants to make informed decisions. This article examines the informational efficiency of the European Union's and China's carbon markets, including China's pilot markets. This study is, to the best of our knowledge, the first to assess the efficiency of China's national carbon market, which began operations in July 2021. We use the novel efficiency measure proposed by Tran and Leirvik (2019). This robust indicator allows not only the assessment of market efficiency or inefficiency but also provides a means to quantify the level of efficiency over time.

Our results can be summarized as follows: China's national market has been notably more inefficient in its first two years of operation compared to the EU's carbon market. However, the level of inefficiency observed in China's ETS is similar to that experienced by the EU market in its initial years. The EU market has alternated between efficient and inefficient phases, achieving a state of efficiency since 2018, though with some variability. As for China's pilot markets, the majority have operated inefficiently; exceptions include the Shanghai market, which remained efficient from 2016 until early 2020, and the Beijing and Tianjin markets, which displayed periods of efficiency from mid-2016 to early 2019 and early 2017 to mid-2018, respectively, and have sustained efficiency since mid-2020. In the most recent sample period, Beijing has shown the highest levels of efficiency, and, overall, Tianjin and Shanghai have achieved the highest average efficiency levels among the pilot markets. The COVID-19 pandemic does not appear to have been associated with a substantial deterioration in the informational efficiency of China's pilot markets. During this period, the EU market experienced a slight decline in efficiency, yet it remained efficient. Overall, the observed shifts in efficiency levels over time, with various markets transitioning between efficiency and inefficiency, suggest that the Adaptive Market Hypothesis offers a more accurate framework for describing the evolution of the markets under analysis.

These findings hold significance for various stakeholders. From a portfolio investment perspective, the informational inefficiency observed in most of China's pilot markets and the national carbon market suggests that predictable price patterns may persist in these markets. However, the presence of informational inefficiency does not, by itself, establish that investors can obtain abnormal risk-adjusted returns after accounting for transaction costs, risk, and other market frictions. The main implication for investors is therefore the need for caution when interpreting carbon-price signals in less-efficient markets, rather than assuming that inefficiency necessarily represents a profitable trading opportunity.

For enterprises facing high marginal abatement and investment costs, the inefficiency identified in the carbon markets in our sample may reduce the reliability of carbon prices as signals for compliance, risk management, and long-term investment decisions. This consideration is particularly relevant for firms making capital-intensive low-carbon investments, for which expectations regarding future carbon costs are important. However,

our empirical analysis does not establish a causal relationship between market inefficiency and firms' investment decisions.

From a regulatory perspective, the persistent inefficiency observed in China's national ETS during its first two years, together with the substantial heterogeneity across the pilot markets, suggests that policy priorities should focus on strengthening the conditions that support information aggregation and price discovery. Importantly, the empirical findings point to different priorities in the short and long term. In the short term, the emphasis should be on improving the information environment and participants' ability to process market information. In the longer term, policy should focus on developing a deeper, more diversified market, strengthening liquidity and market infrastructure, and drawing on the experience of the regional pilots to improve the national system.

In the short term, two priorities appear particularly relevant. First, the priority should be to improve market transparency and information dissemination. The persistent inefficiency observed in China's national ETS suggests that improving the availability, quality, and timeliness of market-relevant information may help participants incorporate information into prices more effectively. Information regarding covered companies and transaction details should be accessible within a unified, reliable, and comprehensive database that provides accurate carbon emissions data. This database should be easy to access and interpret, and available to market participants. In addition, information concerning regulatory changes, allowance allocation, compliance requirements, and other factors affecting allowance supply and demand should be communicated in a timely and standardized manner. The launch of China's National Carbon Trading Market Management Platform in February 2023 reflects an effort to address these needs. This platform now compiles emission data from major emitters. Given that the sample period ends in September 2023, future research will be needed to determine whether the platform and subsequent improvements in emissions-data management have translated into measurable improvements in market efficiency.

Second, given the positive relationship between market liquidity and efficiency observed in studies by Ibikunle *et al.* (2016) and Zhong *et al.* (2023), among others, enhancing liquidity in the carbon market is essential to creating a more attractive trading environment. Poor liquidity compromises the market's efficiency and price discovery function, making it difficult to determine true market prices. Moreover, low liquidity disrupts transaction dynamics by failing to meet corporate demand, ultimately hindering companies' compliance efforts. Therefore, strategies to stimulate enterprise engagement and strengthen the market's role in resource allocation are crucial to boost market vitality and efficiency. One approach to improving liquidity is to encourage market participation by raising carbon asset awareness among managers and enhancing investor literacy. Corporate carbon asset managers' limited awareness of effective carbon asset management may lead firms to retain allowances as a risk-hedging tool rather than actively trading them. Fostering awareness of carbon trading can also be achieved through tax incentives and subsidies. Real progress in market efficiency requires cultivating knowledgeable carbon asset management professionals and encouraging firms to act as genuine carbon asset managers, ensuring the structured operation of the carbon trading market. The Chinese government's initiatives to promote market engagement, including numerous training sessions for key emitters and online programs that have reached over 10,000 participants in 2023, seem to be consistent with these goals. Additionally, the recent formation of an expert panel for China's national carbon trading market, aimed at providing prompt support on technical and policy issues encountered by participants (Ministry of

Ecology and Environment of the People's Republic of China, 2024), may be instrumental in enhancing market efficiency, aligning with the improvements advocated in this study.

The evidence from the pilot markets also suggests that liquidity-enhancing policies should be tailored to regional market conditions rather than implemented uniformly. The substantial differences in efficiency across the pilots indicate that a one-size-fits-all approach may be inappropriate. In particular, the relatively higher efficiency observed in Beijing, Tianjin, and Shanghai provides a basis for examining whether institutional practices, trading arrangements, participants' experience, or market infrastructure in these markets can offer lessons for the further development of China's national ETS. Such lessons should be evaluated carefully, however, because the present study does not identify which specific institutional characteristics account for the differences in AMIM across pilot markets.

In the longer term, China's policy objective should therefore be to develop a deeper and more diversified carbon market while preserving market integrity. This could involve gradually broadening participation, strengthening secondary-market infrastructure, and developing mechanisms that enable market participants to manage carbon price risk more effectively. Broader participation should not be pursued solely to increase trading volume; rather, it should contribute to greater liquidity and information aggregation while maintaining appropriate safeguards against excessive speculation and market manipulation. The more developed participant structure and secondary-market infrastructure of the EU ETS provide a useful benchmark in this respect, although China's institutional development should reflect its own regulatory and economic context.

Furthermore, a more transparent legal framework is essential to clearly identify practices that undermine market integrity, establishing penalties that are substantial enough to deter such actions. Effective implementation of carbon trading policies requires a binding legal framework that functions as a strong legal deterrent. If penalties are minimal and the legal enforcement of policy is weak, companies may choose not to meet carbon reduction requirements due to associated costs. This reluctance could also lead to concerns about asymmetric transactions among market participants, ultimately reducing market liquidity. Efforts appear to be underway to strengthen the legal framework governing activities in China's carbon market. Indeed, on January 25, 2024, the Interim Regulations for the Management of Carbon Emission Trading were enacted, taking effect on May 1, 2024. These regulations represent China's first specialized climate-change legislation, aiming to clarify the legal responsibilities of various entities (including emitting organizations, registry agencies, and trading institutions) and to introduce more stringent penalties for actions such as failing to surrender carbon allowances and engaging in emissions data fraud. Despite the intentions behind these measures, it is essential to recognize that their concrete impact can only be assessed through future empirical studies.

The time-varying nature of the efficiency estimates also has an important policy implication. Because market efficiency changes over time rather than remaining permanently at a particular level, regulatory authorities should monitor market quality on an ongoing basis rather than relying exclusively on periodic assessments of trading volume or compliance. Indicators of liquidity, trading activity, market participation, and informational efficiency could be incorporated into a broader framework for monitoring the development of China's carbon market. Such monitoring would allow emerging periods of persistent inefficiency to be identified and addressed before they become structural features of the market.

Taken together, the findings suggest that China's policy priorities should evolve as the national ETS matures. In the short term, improving data quality, transparency, regulatory communication, and participant expertise should be prioritized. In the longer term, efforts should focus on deepening liquidity, broadening participation, strengthening market infrastructure, and drawing systematically on the experience of the regional pilots. These measures should be regarded as mechanisms that may support price discovery rather than as guaranteed solutions, since the present study does not directly estimate their causal effects on informational efficiency.

This study has several limitations that should be considered when interpreting the findings. First, the analysis focuses on informational efficiency as measured by the AMIM and therefore does not directly examine the specific mechanisms through which market characteristics such as liquidity, market participation, regulatory changes, and investor behavior affect efficiency. Second, although the study compares the EU and Chinese carbon markets and identifies differences in their efficiency dynamics, the empirical design does not allow us to establish causal effects of market maturity, institutional development, liquidity, or regulatory interventions on AMIM. Third, the analysis of the COVID-19 period is based on the evolution of AMIM around the pandemic and does not constitute a formal causal identification of the pandemic's effect on market efficiency. Finally, the sample period ends in September 2023 and therefore does not capture the effects of subsequent institutional and regulatory developments in China's national carbon market, including the implementation of the Interim Regulations for the Management of Carbon Emission Trading in May 2024.

Much remains to be explored regarding the informational efficiency of carbon markets. Future research could address these limitations in several specific directions. First, panel-data or event-study approaches could be used to examine whether changes in liquidity, market participation, allowance-allocation rules, or other institutional characteristics are systematically associated with changes in AMIM across Chinese markets. Second, the implementation dates of major regulatory reforms, including the 2024 Interim Regulations and improvements in emissions-data management, could provide quasi-experimental settings for identifying their effects on informational efficiency. Third, future studies could extend the sample beyond September 2023 to assess whether the continued development of China's national ETS has been accompanied by improvements in efficiency and whether the patterns identified in the pilot markets persist after their integration into the broader national framework. Fourth, the COVID-19 episode could be examined using formal event-study, difference-in-differences, or other identification strategies to distinguish pandemic effects from concurrent changes in market conditions. Fifth, future research could investigate the role of investor and participant composition more directly by examining whether differences in the participation of compliance entities, financial institutions, and other market participants are associated with differences in price discovery and AMIM. Finally, cross-market research could compare China and the EU with other established and emerging carbon markets to determine whether the adaptive patterns identified in this study generalize across different institutional settings.

From a methodological standpoint, given the differences between carbon markets and traditional financial markets, developing specialized statistical techniques tailored to carbon market efficiency modeling could offer insightful advances in this field. In particular, future methodological research could complement AMIM with measures that capture nonlinear dependence, liquidity conditions, or structural changes in carbon markets, thereby providing

a more comprehensive assessment of the mechanisms underlying time-varying informational efficiency.

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The paper.

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