The efficiency of CO₂ market in the phase III EU ETS: analyzing in the context of a dynamic approach

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Abstract

This study has investigated the changing efficiency for the phase III EU ETS CO₂ market using the daily historical data of allowance future prices and coverage from August 2015 to December 2020. We have applied two alternative tests for checking dependency by linear and nonlinear methods to achieve this goal, including generalized spectral (*GS*) and automatic portmanteau (*AQ*). Also, we had a comprehensive look at the carbon market evolution and the EU ETS scheme development over time. The analysis of observed results validates the adaptive market hypothesis (AMH) in the market, which corresponds with the oscillatory behavior of the applied test statistics' *p*-values. The other aspect of the study was to analyze the existence of evolutionary behavior on the market. To reach this purpose, we checked the results by applying a rolling window technique with four different time windows (50, 100, 150, and 250 days) on the test statistics in harmony with the adaptive market hypothesis. The obtained results show that overall, market efficiency has been improved by implementing higher window lengths.

Keywords Emission trading schemes · Market efficiency · Adaptive market hypothesis · Rolling sample

Introduction

Emphasizing that climate change is recognized as an environmental challenge and an economic one, numerous countries and regions have introduced some economic tools to battle against the adverse effects of climate change. In this context, the most renowned policies presented are command and control actions and carbon pricing mechanisms—both of these two methods form a cost component for firms responsible for environmental destruction. Meanwhile, climate change is regarded as a market failure that is an outcome of not being able to mirror its costs into the pricing procedure.

Among these practices, emission trading schemes arise to the front as more potent emission reduction tools since their capability to yield certainty in emission reduction is detected. The international community has also acknowledged the significance of these schemes. Because of this reason, this

mechanism, provisions, and related regulations have been involved in all binding international agreements established in the framework of climate change.

As climate change is an international concern, several global initiatives and commitments have been adopted until now. Numerous meetings were organized to discover a solution with many countries' involvement to remove or decrease climate change's adverse effects.

Theoretically, emissions trading schemes, also referred to as “cap and trade” schemes, offer a cost-effective tool of reducing emissions in a way that allows for more flexibility in how participants decrease their emissions in comparison to a carbon tax. Under “cap and trade” schemes, a government sets an overall limit on the level of emissions of gas or pollutant. Within the limit, allowances are formed, consistent with one unit of emissions. Participants in the scheme should attain allowances directly from the government or other participants and surrender sufficient allowances to wrap their emissions over a specified period. Cap and trade schemes permit participants to select whether to invest in emissions reduction or buying additional allowances to cover their requirements. On the other side, if a participant has excess allowances, they can sell them to others (Grantham Research Institute on Climate Change and the Environment 2018). According to Dales (2002), property rights in climate change are called

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Table 1 Emission trading implementations and price levels in 2017

Country/region	Price level (\$/tCO ₂ e)	Country/region	Price level (\$/tCO ₂ e)
South Korea ETS	21	Saitama ETS	6
EU ETS	16	Shanghai pilot ETS	6
California CaT	15	Tokyo CaT	6
New Zealand ETS	15	Chongqing pilot ETS	4
Ontario CaT	15	RGGI	4
Québec CaT	15	Fujian pilot ETS	3
Beijing pilot ETS	9	Guangdong pilot ETS	2
Switzerland ETS	8	Hubei pilot ETS	2
Shenzhen pilot ETS	7	Tianjin pilot ETS	1

Source: World Bank and Ecofys, 2018

emission allowances. The system reaches the market solution through transferable quotas. In doing so, the regulatory authority has no responsibility except to regulate only the total GHG ceiling and allocate emissions allowances in this framework (Hahn and Stavins 2011). Cap and trade schemes have their roots in lay-down leaded fuel in the USA in the early 1980s. A tradable lead credit program was shaped to aid small refineries to meet their lead reduction goals when more significant operations could apply lead reduction technology at a lower cost (Ellerman et al. 2003; Newell and Rogers 2003). In Table 1, emission trading schemes that are currently applied and price levels in these markets are shown (World Bank and Ecofys, 2018).

In the framework of the design of an ETS, defining an upper limit¹, coverage, and scope and then allocating allowances is essential. In this context, every allowance is equal to 1 ton of emissions. The prices of allowance are determined in the market where they are traded. The market price and the polluter's willingness to pay for it define which economic players will keep polluting and which actors will invest in emission reduction technologies (Weishaar 2014). Emissions trading guarantees certainty on the emission mitigation level rather than its cost because, in this scheme, the cap for emission level is crucial. Therefore, the ETS is considered by numerous economists and politicians a market-based and productive policy tool (Jaehn and Letmathe 2010).

Each facility exposed to ETS regulation must hold sufficient allowances equal to the volume of originating emissions. In the beginning, the allowances are allocated to facilities by the selected authority concerning different criteria like historical emissions of the facility, sectoral benchmark, or output-based allocation for each facility. Moreover, these allowances can be allocated without restrictions or by auction. While the free allocation facilities accept just the cost of emission allowances, the government's income is also generated in the

auctioning and it is generally expended for environmental and low-carbon investments. After the initial allocation of allowances, which could also be named the primary market, if these facilities demand additional allowances, they should trade in the secondary market.

The prices of the emission allowances are determined in the secondary market. If the ceiling is assigned at low levels, the price will ascend and therefore a robust signal will be made to decrease emissions or vice-a-versa. This criterion will guarantee that products that have lesser emissions are preferred. Consequently, the market participants' long-run predictability and investment choices can be formed by predetermining and declaring the upper bound. When the world's price trends by 2017 are observed, prices vary from 1 USD/tCO₂e to 20 USD/tCO₂e. The highest allowance price is seen in South Korea, and the lowest is in the Tianjin pilot ETS in China (World Bank and Ecofys, 2018).

Additionally, the facilities can utilize national or international emission units with the prescribed characteristics. The Kyoto Protocol covers emission reduction units (ERUs) and certified emission reductions (CERs) to satisfy their obligations. Thus, as incentives are generated for cleaner energy projects, flexibility is provided to businesses under ETS to satisfy emissions reduction commitments.²

One of the subjects that can be considered concerning the carbon market and its characteristics is market efficiency. Due to the existing issues in the financial markets like transaction costs, information asymmetry, and behavioral biases of investors, which have significant consequences on market efficiency, the topic of market efficiency is of tremendous interest to emissions-intensive businesses, risk managers, policymakers, and also investors in an emerging group of energy and carbon hedge funds (Krishnamurti and Hoque, 2011). Therefore, research on the market efficiency has an evident implication for

¹ An upper bound is imposed on the total volume of emissions in the economy, and it is clarified regarding this ceiling.

² In emission trading systems, emission allowances allocated to covered facilities could be kept for later use if they exceed the need in the relevant period. This process is called banking. This flexibility provided by the trading system ensures that emissions are reduced most cost-effectively.

more development of the carbon markets and ETSs worldwide.

On the other hand, analyzing the efficiency of carbon markets also has substantial implications for some issues in the energy sector, such as energy management and the development of novel energy technologies. For example, it has been found that carbon markets can impact the energy consumption patterns, and as a consequence of the robust connection between market efficiency and the validity of price information, CO₂ markets can influence diverse types of power generation. Therefore, an efficient carbon transaction procedure can provide backing low-carbon powers (Zhang et al. 2018). Moreover, numerous researches also advocate that the efficiency of carbon markets can influence the technology choice (Tian et al. 2017) and policy supports of energy (Shahnazari et al. 2017), and so considerably motivate the path of technology development in the energy area. Thus, we can infer that a better knowledge of the carbon market efficiencies can deliver significant insights into other general energy and environmental issues.

Market efficiency and the adaptive market hypothesis (AMH)

The idea of analyzing efficiency in the markets has been discussed over the past years since Fama (1970) introduced the brilliant concept “The Efficient Market Hypothesis (EMH).” In the initial years, this topic was focused on the notion of random processes of financial price fluctuations. This concept reasoned that prices should pursue a random walk process when the market is efficient since all available information concerning prices is precisely mirrored in the price. Therefore, it is impossible to forecast prices based on a recent series of information. Hence, collecting information in a market with an efficient state is ineffective because new information will immediately change the prices. Grossman and Stiglitz (1980) argue that a perfect market is unfeasible since if prices expressed complete existing information, traders would have no motivation to obtain costly information. In other words, if a market shows signs of efficiency in the weak form, returns are not forecastable and should be independent of each other (Fama, 1970). Conversely, if prices are forecastable and dependent, traders can utilize the information to obtain unusual gains.

Several papers have displayed that assets’ price does not accompany random walks, and price fluctuations are forecastable (Fama and French 1988). This finding led to a burgeoning of documentation scrutinizing the efficient market hypothesis’s viability in different economies (see Opong et al. 1999; Borges 2010). They apply several tests to assess whether a market is efficient beyond certain predetermined times, with the result that analyzing efficiency in the market is categorized as all-or-nothing circumstances. There prevails a

dispute between the latest literature and EMH due to studies discovering that market oddities already existed as data possess the feature of dependency (Shahid and Mehmood 2015). These researches display that there exist several abnormal profits in the securities market. Grossman and Stiglitz (1980) debate that it is impracticable for a financial market to be perfectly efficient, considering that investors do not gain price information if profit-making prospects were not accessible and markets are efficient. In terms of the impracticability of achieving a completely efficient market, Campbell et al. (1998) suggest the notion of relative efficiency instead of perfect efficiency that causes an oscillation from analyzing the market’s efficiency from an “all-or-nothing condition” to evaluate it throughout the period.

Moreover, the findings and recently developed empirical research indicate that the market’s efficiency changes as time goes on (Lim and Brooks 2011), therefore, challenging the viability of the EMH and that it does not regularly hold.

Furthermore, Lo (2004) expands on the existing biases in behavior founded on the notion of bounded rationality, which Simon (1955) introduced. By considering the psychological side of the EMH argument, an unorthodox approach might be needed instead of the established logical approach in mainstream economics, which is limited by logicity for optimizing decisions. The latest initiation utilized evolving behavior to capital markets and was advocated by Farmer and Lo (1999) and Farmer (2002). In this respect, approaching a balanced situation, which is crucial to the efficient market hypothesis, is neither likely to occur nor assured in the time to come. Inherently, it is false to assume that the market has to shift direction into a perfect balanced situation or efficient one. Instead, the novel concept directs more complex market dynamism, like cycles, manias, crashes, bubbles, and other events in the capital market (Lo 2005).

From this perspective, Lo (2004) presented the adaptive market hypothesis (AMH) notion to exhibit that the market’s efficiency and inefficiencies exist side by side in rationally stable conduct. Also, the AMH permits checking the evolving manner of market efficiency with time and not an all or none status. As players in the market adapt to an evolving situation, they rely on the rule of thumb to make their financial decisions.

In the following, some of the recent researches focused on analyzing financial assets’ market efficiency through AMH have been stated: Ghazani and Ebrahimi (2019) investigate the existence of the adaptive market hypothesis (AMH) by utilizing daily returns from 2003 to 2018 on the three crude oils (Brent, WTI, and OPEC basket). The findings indicate that the WTI and the Brent oil markets show the topmost efficiency levels. Also, OPEC basket behavior characterizes that by moving toward longer window lengths, the extent of compliance with AMH diminishes.

Noda (2020) investigates whether the market efficiency of selected cryptocurrencies (Bitcoin and Ethereum) changes over time based on the AMH. He measures the extent of market efficiency by applying a time-varying model that does not have any type of dependency upon sample size, different from prior studies that utilized common approaches. The empirical findings indicate that (1) the extent of market efficiency fluctuates with time in the markets, (2) the level of Bitcoin's market efficiency is higher than that of Ethereum over most of the periods, and (3) a market with high market liquidity has been evolving. Generally, the findings support the AMH for the most well-established cryptocurrency market.

Tripathi et al. (2020) investigate the adaptive market hypothesis (AMH) for 21 major global market indices for 1998–2018. They employed quantile-regression methodology to scrutinize the market efficiency of 16 financial markets. The findings display that higher quantiles' returns are negatively auto-correlated, and those in lower quantiles are positively auto-correlated. In general, market efficiency seems to be time-varying and conditioned to the state of the market. Moreover, the analysis suggests significant evidence supporting the AMH for a considerable number of financial markets.

Varghese and Madhavan (2020) investigate the long memory dynamics in crude oil markets from an adaptive market hypothesis (AMH) perspective. In doing so, they selected the three benchmark crude oils, namely, WTI, Brent, and Dubai crude prices, to a rolling Hurst exponent analysis. Their findings show that the WTI market is relatively efficient, followed by Brent and Dubai markets. Furthermore, by applying an extensive dataset of over 36 years, they realize crude oil markets to be efficient most of the time, only to be interposed with transitory and short-lived periods of market inefficiency. Therefore, in this study, we have tried to assess market efficiency's adaptive behavior about EU ETS CO₂ Allowance prices in the AMH framework.

This study's main contributions are as follows: initially, this article checks the AMH concept on EU ETS CO₂ Allowance prices to scrutinize the data's return predictability by applying well-known linear and nonlinear statistical techniques. These techniques can identify any time-varying serial dependency in mean, permit an unspecified structure of conditional heteroscedasticity, and confirm the swinging manner of efficiency. Secondly, this paper uses a "rolling sample" method with diverse window sizes to replace a prearranged event, typically encountered with some criticism.

The European Union Emission Trading Scheme (EU ETS)

The EU ETS is defined as the first primary CO₂ market and still one of the largest cap-and-trade schemes targeting

emission mitigation. The EU Emissions Trading System (EU ETS) is the basis of the EU's efforts to alleviate climate change and the central mechanism for shrinking its greenhouse gas (GHG) emissions across various sectors like power, industry, and aviation (Action 2018). It is the first and most exceptional emissions trading system globally, covering 45% of the EU's GHG emissions, accounting for over 75% of international carbon trading. The EU ETS is an obligatory "cap and trade scheme" which adjusts greenhouse gas emissions from over 11,000 installations across 31 countries in the European Economic Area (EEA, EU28 + Liechtenstein, Iceland, and Norway) (UK Government 2018). The EU ETS, which unfolded operation in 2005, is currently in phase III, covering the periods during 2013 and 2020, and preparations are proceeding for phase IV (2021–2030). Allowances created under the EU ETS are subjected to trade in over-the-counter (OTC), spot and futures markets. European Energy Exchange (EEX), located in Germany, and the InterContinental Exchange (ICE), located in the UK, are applied for EU ETS trading operations. The emission allowances are quoted to these markets under the name of European Union Allowances (EUAs). The scheme is planned to support the EU in achieving both its instant and longer-term emissions mitigation targets by "promoting reductions of emissions in a cost-effective and economically efficient manner." Additionally, the scheme aims to be a notable driver for the Union and the investments in clean technology and low carbon development, particularly in developing countries, to smooth the transition toward a low carbon economic structure.

We can observe that each phase has its specific characteristics and specifications by looking carefully at prices' history. For example, in phase I, there was no accurate emission data of facilities and the absence of bankable allowances; the pricing conduct was different from other phases. Another instance is defining the cap level left to each Member state in phases I and II by National Allocation Plans (NAPs). This arrangement has been altered in phase III, and it is decided that this cap should be shared and regulated by Commission. EUA's prices (Fig. 1), which have been exchanged from 2005 to 2017 on the European CO₂ market, alternated in the range [0, 30] US dollars and mostly at low values (Burtraw and Themann 2019). This pattern transformed entirely in 2018 when prices elevated severely from 9 to above 25 US dollars between January and September. That kind of price trajectory is unexpected, considering the particular structure of the cap-and-trade scheme. The renewed design of the EU ETS demands a mitigation factor of 2.2% annually that would cause a peak of null emissions in the next four decades (Edenhofer et al. 2017). Due to this factor, the rational market participants should have a robust motivation to steadily trail more cost reduction actions and buy CO₂ allowances from others to accumulate a bank accessible once the scheme is more rigid in the coming years. This sensible manner has to be evident in

Fig. 1 EU ETS CO₂ Allowance prices in dollars (2005–2018). Sources: Thomson Reuters (spot prices for phases I and II); ICE (future prices for phase III)

a price route that consistently rises as times go on (Burtraw and Themann 2019).

As an alternative, allowance prices stayed obsessively down in most of the three phases, and surge strongly in a short time. One explanation of this absence of cohesiveness is that market players are significantly sensitive to political occasions, and allowance prices are a trivial representation of their assurance in the ongoing policy scheme and participants' dedication to the policy. It seems that member states had a drastic credibility gap that the scheme would be into force in the future or that the level of allowances for emissions could be rarer in the forthcoming. This perspective looks to have altered currently in the wake of the latest overhaul activities. This kind of practice is not exclusive to the EU. Each emissions market throughout the globe has observed price trajectories under expectations, involving short-run exemptions, where prices climbed ahead of tumbling further to lower levels (Burtraw and Keyes 2018).

As aforementioned, the scheme is currently in phase III and the forthcoming subsection delivers a thorough examination of the essential characteristics and features of this phase.

Phase III (2013–2020)

In comparison to earlier periods, phase III of the EU ETS has become distinct in the wake of significant regulations. In this period, European Union Member States accepted the 2030 CEF framework, in which the expected consequence for the EU ETS had been stated as cutting emissions from sectors captured by the EU ETS by 43% compared to 2005. Afterward, from 2021 forward, the ceiling will be lowered by more than 2% annually until 2030 (Action 2015). To attain these goals, the players have taken a significant reform for the trading scheme into action. To that end, as a replacement for a nationally determined cap, a typical Europe-wide emission cap has been implemented for the third period of the EU ETS. In this context, in phase III, it is predicted that the cap will be lessened through a linear mitigation factor of 1.74%

annually to alleviate emission by 21% in 2020 compared with the level of 2005 (European Commission, 2015). Furthermore, while the free allocation for industrial facilities (except the power generation sector) is still in charge, free allocations of emission allowances for the remainder of facilities have been reduced, and auctioning has been chosen as the current allocation method.

During the second period of the EU ETS, the system was troubled by the massive allowance surplus due to slowdowns in the European economy and high international credit imports, which reduced EUA prices. To conquer the excessive surplus of allowances and also to correct the system for potential market inefficiencies in the future, EU regulators applied two main policy measures (De Clara and Mayr 2018):

- Backloading,
- The Market Stability Reserve

Backloading was anticipated to address the imbalance in the market of EUAs in the brief period. It was also postponing the bidding of about one billion allowances between 2014 and 2016 throughout phase III. With this measure, while the number of allowances auctioned in phase III has not been reduced, it is aimed to set the supply side of the market to avert price collapse. As a more general and long-run resolution to enhance the market's functioning, the European Commission suggested the Market Stability Reserve (MSR) that would systematically and momentarily eliminate oversupply from the market. This action is being scheduled as a component of the ETS revision for phase IV. MSR aims to tackle the glut of EUAs and enhance the scheme's resiliency to disturbances by fine-tuning the number of allowances to be auctioned (European Commission, 2018). Applying these innovative attributes in phase III allows the scheme to switch from the temporary training years toward a thoroughly operative EU-wide policy instrument (IETA 2015). In this phase, prices swung between 3.4 Euro/tCO₂e and 9.6 Euro/tCO₂e. The most notable variation in prices had been realized in December 2015 when the Paris Agreement had been concluded. Every month, the EUA prices had declined by almost 43%

to 4.98 Euro/tCO₂e in February 2016 from 8.67 Euro/tCO₂e level in November 2015. However, after April 2017, this trend had been upturned. The EUA prices had soared from 4.9 Euro/tCO₂e to 8.15 Euro/tCO₂e in about nine months. The fundamental changes in the EU ETS from Phase II to Phase III have been illustrated in Table 2.

Literature review

By looking carefully at the literature on the topic of market efficiency and studies that took place in this area, it can be seen that several methods have been proposed to examine the market efficiency in carbon markets and we can classify them into several distinct categories. They include methods that rely on variance ratio (VR) tests (Daskalakis and Markellos 2008; Ibikunle et al. 2012; Montagnoli and De Vries 2010; Niblock and Harrison 2013; Yang et al. 2018; Zhang et al. 2020; Zhou et al. 2019), cost of carry models (Charles et al. 2013; Joyeux and Milunovich 2010), and the profitability of trading strategies (Aatola et al. 2014; Daskalakis and Markellos 2008; Daskalakis 2013; Niblock and Harrison 2013), and the methods based on multifractality tests and intermittency coefficient (Fan et al. 2019; Sattarhoff and Gronwald 2018). In what follows, we tried to analyze the ideas presented in each of the mentioned studies.

Daskalakis and Markellos (2008) examined the EU allowances for CO₂ emission's market efficiency. In doing so, the spot and derivatives market data are scrutinized from Powermex, Nord Pool, and ECX, the three major exchanges in the context of EU ETS. The findings propose that the conduct of considered markets is not in compliance with weak-form efficiency. This issue could be resulting from the EU ETS's infancy, and the constraints are imposed on short-selling and "banking" of emission allowances.

Joyeux and Milunovich (2010) employ the cost-of-carry method to examine the degree of efficiency in the EU futures market for CO₂ allowances from June 2005 to December 2007 and discover some corroboration of enhancement in market efficiency during the period.

Montagnoli and De Vries (2010) used the variance ratio tests to verify the efficient market hypothesis (EMH) in the market for CO₂ emission allowances in two phases (phase I and phase II) of the EU ETS. Their results show that phase I was inefficient, considering that the initial stage under phase II displays indications of reinstating market efficiency.

Charles et al. (2013) investigated the connection between futures and spot prices in the EU CO₂ markets through the cost-of-carry model to explore the magnitude of market efficiency. A trio of major European markets (including BlueNext, EEX, and ECX) is studied under phase II, wrapping between March 2009 and January 2012. The results

Table 2 The main adjustments in the EU ETS from phase II to phase III

<ul style="list-style-type: none"> ➤ The introduction of a unique Europe-wide emissions ceiling, to be mitigated by 1.74% per year up to 2020 (referred to as a linear reduction factor, LRF). ➤ Free allocation to industrial facilities (except for power generation) was determined using 'benchmarks,' which are calculated based on the installation's output/input. Any additional allowances needed are to be obtained by trading. ➤ The steady phase-out of free allocation over Phase III, to be replaced with auctioning as the primary method of allowance allocation. Around 40% of EUAs were distributed by auction, covered by the EU ETS Auctioning Regulation. ➤ The Union Registry was established as a central record of all allowance holdings and transactions. ➤ The NER300 innovation fund was established, using revenue from auctions to fund investment into low-carbon technologies.
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Source: The Oxford Institute for Energy Studies, 2018

display that the method of cost-of-carry is nullified for CO₂ markets and all maturities, suggesting that neither contract is priced as stated by this method. The lack of relationship under the cost-of-carry model can be characterized as a sign of inefficiency in the market and may provide arbitrage opportunities in the carbon market.

Daskalakis (2013) analyze the efficiency of four CO₂ emission allowance futures traded in the Intercontinental Exchange (ICE) between 2008 and 2011. His findings suggest that the EU CO₂ market is showing a weak form of market efficiency. Niblock and Harrison (2013) investigate the weak-form efficiency situation of the EU CO₂ market over durations of persistent volatility, complexity, and uncertainty. They divided the data into two diverse crisis periods (global financial crisis (GFC) and the EU sovereign debt crisis). They show that regardless of constant volatility in the market, uncertainty in the economics, and the vagueness in the global climate change policy, the European Union Emission Trading Scheme is approaching a more weak-form efficient state.

Ibikunle et al. (2012) investigate liquidity and efficiency in the market on the European Climate Exchange (ECX) through implementing Chordia et al.'s (2008) notion of short-term price foreseeability as contradictory evidence of market efficiency. They identify a robust connection between market efficiency and liquidity so that when differences are minor, the predictability of returns abates.

Aatola et al. (2014) investigate the EU carbon market in terms of informational efficiency by imitating this market's trading. They find that there have been prospects for profitable opportunities in the European Union carbon market for 2008–2010. This finding implies that the European emission trading market displays durations with no informational efficiency.

Zhao et al. (2017) study the CO₂ emission market of four typical localities in China based on the efficient market theory and fair game method and by developing the statistical tests. Their findings reveal that at first, the CO₂ emission market in China has only reached weak-form efficiency, whereas the semi-strong and the strong form of efficiency have not been attained. Second, with the growth of the scale of the market, the rising of trading volume, the CO₂ emission market would get together from an inefficient state to a weak form one steadily, and the market for carbon trading in China illustrates indications of reinstating efficiency in the market.

Sattarhoff and Gronwald (2018) propose a new standard for assessing efficiency in the EU ETS market called intermittency multiplier. They demonstrate that the market turns into a more efficient state over time. Moreover, the extent of efficiency in the market is similar to the US financial market; only for one period, the market's efficiency level is recognized to be higher.

Yang et al. (2018) utilize Lo MacKinlay's several variance ratio tests to examine and analyze the characteristics of the EU CO₂ market. The findings of this paper demonstrate, in the 12-

year evolution of the EU ETS, just the returns in phase II following the Martingale Process, presenting an efficient market in the weak form. In contrast, phase I and phase III fall short to carries attributes of an efficient market.

Fan et al. (2019) check the multifractality and efficiency of several pilots in the CO₂ market of China by applying the multifractal detrended fluctuation analysis (MFDFA) method. They evaluate the efficiencies in these markets by utilizing an indicator that they introduced based on the generalized Hurst exponents, and the findings imply prevalent inefficiencies among pilot markets. However, the condition of the pilots has been enhancing over time in terms of efficiency.

Zhou et al. (2019) scrutinize the level of efficiency in several CO₂ trading markets in China. The results show that most CO₂ markets are inefficient, and only Hubei, Fujian, and Beijing markets illustrate market efficiency.

Zhang et al. (2020) apply four robust variance ratio (VR) tests to deliver fundamental alterations and investigate the efficiency of China's several regional carbon markets in diverse stages. The obtained results from the VR tests show a weak-form efficient state in most of China's regional carbon markets. In conclusion, they offer numerous recommendations to enhance the efficiency of China's carbon markets, including advancing the market design, forming information platforms, and strengthening legislation.

By scrutinizing the studies mentioned above on market efficiency in the carbon market, it can be seen that all of the studies generally are implemented on the concept of EMH. However, as presented in detail in "Market efficiency and the adaptive market hypothesis (AMH)" of this study, analyzing the market efficiency within the EMH framework implies some limitations. Because as discussed earlier, recently developed empirical research indicates that the market's efficiency changes as time goes on (Lim and Brooks 2011) and, therefore, challenging the viability of the EMH and that it does not regularly hold. On the other hand, the AMH, as a novel concept, directs more complex market dynamism, like cycles, crashes, bubbles, and other events in the market. Moreover, it exhibits that the market's efficiency and inefficiencies coexist in stable conduct and permits to check the evolving manner of market efficiency with time and not an all or none status. As a result, in this study, we focused on using the AMH approach, which provides a more accurate understanding of market efficiency developments over time.

The rest of this article is structured as follows: "Methodology" exhibits the methodology. Then, "Analyzing the data" illustrates the data and relevant examination. Next, the evaluation of the obtained findings has been offered in "Analyzing the empirical results," and lastly, "Conclusion" presents the study's conclusions.

Methodology

The generalized spectral test

The generalized spectral (GS) test introduced by Escanciano and Velasco (2006) is a non-parametric method defined to determine dependencies in time series with stationary behavior.

In this paper, we trail this test as employed in Lazăr et al. (2012): by considering Y_t as a persistent time series of returns. The martingale difference hypothesis (MDH) states that the values of returns are not foreseeable. Therefore Y_t is a sequence of martingale differences when we are unable to forecast its amount in the forthcoming. The H_0 hypothesis for the return series of an MDH is studied versus the alternative hypothesis by implementing a pairwise technique.

$$\begin{aligned} H_0 : m_\theta(y) &= 0 \quad \text{for all } \theta \geq 1 \quad ; \quad m_\theta(y) = E[Y_t - \mu] \\ H_1 : P(m_\theta(Y_{t-\theta})) &\neq 0 > 0 \quad \text{for some } \theta \geq 1 \end{aligned} \quad (1)$$

Let $\varphi_\theta(z) = E[(Y_t - \mu)e^{izY_{t-\theta}}]$ be a nonlinear criterion of mean dependency in what respect $z \in \mathbb{R}$. A function with exponential weighting property is applied to define the mean dependency in a nonlinear time series. Accordingly, the above H_0 hypothesis complies with $\varphi_\theta(z) = 0$ for all $\theta \geq 1$. Escanciano and Velasco (2012) utilized the GS distribution function:

$$\begin{aligned} \Upsilon(\psi, z) &= \varphi_0(z)\psi + 2 \\ &\times \sum_{\theta=1}^{\infty} \varphi_\theta(z) [\sin(\theta\pi\psi)/\theta\pi] \quad ; \psi \in [0, 1]. \end{aligned} \quad (2)$$

Table 3 Summary statistics of returns for the EU ETS Allowance prices

Criterion	Results
Mean	0.000443
Median	0.000014
Maximum	0.054274
Minimum	−0.079004
Std. Dev.	0.012721
Skewness	−0.277097
Kurtosis	6.356500
Jarque-Bera	670.7649*
$Q(5)$	7.3671
$Q(10)$	10.810
$Q^2(5)$	115.38
$Q^2(10)$	153.26

* represents the result is significant at one percent. $Q(n)$ and $Q^2(n)$ display the quantity of the Ljung–Box test for returns and its squared values, respectively, distributed as χ^2_1 . The n is the utilized number of lags

The estimate of Υ transforms into

$$\hat{\Upsilon}(\psi, z) = \varphi_0(z)\psi + 2 \sum_{\theta=1}^{n-1} \sqrt{(1-\theta/n)} \hat{\varphi}_\theta \frac{\sin(\theta\pi\psi)}{\theta\pi} \quad (3)$$

where $\hat{\varphi}_\theta = (n-\theta)^{-1} \sum_{t=1+\theta}^n (Y_t - \bar{Y}_{n-\theta}) e^{izY_{t-\theta}}$ and $\sqrt{(1-\theta/n)}$ is a sample finite correction element. Consequently, the generalized spectral distribution function under the H_0 of MDH transforms into $\Upsilon(\psi, z) = \varphi_0(z)\psi$. The method is originated from the variation between $\hat{\Upsilon}(\psi, z)$ and $\Upsilon_0(\psi, z) = \varphi_0(z)\psi$ as follows:

Fig. 2 The return series of daily EU ETS CO₂ Allowance prices

Table 4 The number of rejections for H_0 of test statistics

Test statistic	50		100		150		250	
	0.05*	0.1**	0.05	0.1	0.05	0.1	0.05	0.1
<i>Automatic portmanteau (AQ)</i>	158	243	143	188	73	120	1	12
<i>Generalized spectral (GS)</i>	21	76	53	107	11	43	14	49

*Calculated at a five percent significant level

**Calculated at a 10% significant level

$$S_n(\psi, z) = \sqrt{n/2} [\hat{\Upsilon}(\psi, z) - \hat{\Upsilon}_0(\psi, z)]$$

$$= \sum_{\theta=1}^{n-1} \sqrt{(n-\theta)} \hat{\varphi}_\theta(z) \frac{\sqrt{2} \sin(\theta\pi\psi)}{\theta\pi} \quad (4)$$

We apply a specific norm presented in the equation below and developed by the Cramer-von Mises to scrutinize the distance of $S_n(\psi, z)$ to 0 for the entire imaginable values of ψ and z .

$$D_n^2 = \int_{\mathbb{R}} |S_n(\psi, z)|^2 W(dz) d\psi$$

$$= \sum_{\theta=1}^{n-1} (n-\theta) \frac{1}{(\theta\pi)^2} \int_{\mathbb{R}} |\hat{\varphi}_\theta(z)|^2 W(dz) \quad (5)$$

in case the weighting function $W(\cdot)$ meets the number of moderate requirements. If the regular Gaussian cumulative distribution function is regarded as a weighting function, the following statistics results in:

$$D_n^2 = \sum_{\theta=1}^{n-1} \frac{(n-\theta)}{(\theta\pi)^2} \sum_{t=\theta+1}^n \sum_{s=\theta+1}^n (Y_t - \bar{Y}_{n-\theta}) (Y_s - \bar{Y}_{n-\theta}) \exp\left[-\frac{1}{2} (Y_{t-\theta} - Y_{s-\theta})^2\right] \quad (6)$$

The H_0 of MDH is not accepted when values of D_n^2 are significant. The p -values of D_n^2 test statistics are attained through the phases defined in Escanciano and Velasco (2012). Hence, the test statistic's p -value is measured as the percentage of D_n^{*2} that is greater than D_n^2 .

Automatic portmanteau (AQ) test

For adjustment to the conditional heteroscedasticity typically exhibited by returns in financial data, Lobato et al. (2001) transformed the portmanteau test statistic introduced by Box and Pierce (1970) and resulted in:

$$Q_v^* = n \sum_{\theta=1}^v \tilde{\rho}_\theta^2 \quad ; \quad \tilde{\rho}_\theta^2 = \frac{\hat{\gamma}_\theta^2}{\hat{\gamma}_\theta^2} \quad (7)$$

Given Y_t to be returns series and $\hat{\gamma}_\theta^2 = \frac{1}{n-\theta} \sum_{t=1+\theta}^n (Y_t - \bar{Y})^2 (Y_{t-\theta} - \bar{Y})^2$ is the Y_t 's autocovariance. Moreover, the v is the ideal lag order designated based on the combination of two well-known information criteria (Akaike and the Bayesian). In this context, the test of automatic portmanteau is expressed as:

$$AQ_v^* = n \sum_{\theta=1}^{\hat{v}} \tilde{\rho}_\theta^2 \quad (8)$$

Fig. 3 Analyzing the behavior of market efficiency by AQ tests statistics

Fig. 4 Dynamic conduct of AQ test's p -values in a 50-day time window

The AQ test statistic traces the χ^2_1 distribution asymptotically under the H_0 of no existence foreseeability in return series.

Analyzing the data

In this section of the paper, the statistical analysis of information has been discussed. The data consist of the daily futures prices for carbon emission allowance obtained from the ICE EUA. The data of study spans from 7 August 2015 to 31 December 2020, and also the returns are computed as a difference in daily prices in logarithmic form, i.e., $r_t = (\ln p_t - \ln p_{t-1})$. Figure 2 shows the return series of daily EU ETS CO₂ Allowance prices.

The summary statistics of returns have been presented in Table 3. The results are displaying negative skewness. Also, the level of kurtosis is remarkable and illustrates leptokurtic behavior, and confirms excess kurtosis. The above information shows that the time series of returns are distributed far

from Gaussian, and the substantial result for related test statistics (Jarque-Bera) proves it. Also, the Ljung–Box test for returns and its squared values depicted through $Q(\cdot)$ and $Q^2(\cdot)$ display the significance of serial correlation for the returns.

To investigate the evolving behavior of market efficiency, we implement a rolling window method. It is a suitable technique that can assess the robustness of findings crucial for time series models (Swanson 1998). In this study, four diverse window lengths, 50, 100, 150, and 250 days, have been selected.

Analyzing the empirical results

For this part, we study the status of changing market conditions in terms of efficiency. As revealed in Table 4, the number of results that do not accept H_0 of the test, which, in a sense, characterizes the market's inefficiency, has been declared. The assessment of acquired results and comparing data concerning market efficiency can be critical from two different aspects. Initially, we can find out and check market

Fig. 5 Dynamic conduct of AQ test's p -values in a 100-day time window

Fig. 6 Dynamic conduct of *AQ* test's *p*-values in a 150-day time window

efficiency behavior by varying the window lengths for data (from 50 to 250 days), which expresses the evolutionary and adaptability attitude to the concept of efficiency. On the other hand, we can compare the data and analyze market efficiency based on two linear and nonlinear techniques mentioned in the study.

This section has assessed the study results based on the two diverse methods (including *AQ* and *GS* test statistics). Furthermore, the results are examined in various time windows (50 to 250 days), which help us measure the degree of conformity of results with the AMH. Based on this idea, the evolutionary behavior of data regarding market efficiency and in different periods has been considered. Initially, the results are investigated based on the *AQ* method.

Evaluating the results based on the *AQ* method

In Fig. 3, the process of variation in the number of observations, which indicates that the null hypothesis of the test statistic has not been accepted at two different levels of

significance (5 and 10%), has been declared, and the results illustrate the relative inefficiency of the market for various time windows. As the figure reveals, the null hypothesis's rejections peaked in the 50-day window length, representing the least efficient condition for the market. Afterward, along with the increasing window length, we can observe market efficiency improvement.

Moreover, by looking carefully at the initial observations in Figs. 4, 5, 6, and 7, we can perceive that the market is visibly far away from the efficient condition in which the rejection of the null hypothesis of the *AQ* test confirms it. Moreover, the behavior of the *p*-values over time verifies the getting away from the efficient state. Nevertheless, as visible in Figs. 4 and 5, the market is initially inefficient and then goes out of this situation and moves toward the maximum efficiency and then again back to the inefficient condition. This form of behavior is consistent with the concept of the AMH, which was defined earlier. Indeed, in this case, the data's oscillatory manner (between the efficient and inefficient) can be traced noticeably.

Additionally, by increasing the length of the time window (from 50 to 250 days), the evolving behavior of *p*-values

Fig. 7 Dynamic conduct of *AQ* test's *p*-values in a 250-day time window

Fig. 8 Analyzing the behavior of market efficiency by *GS* tests statistics

becomes apparent, which again confirms the AMH and, as a consequence, the adaptive conduct of CO₂ allowance returns. However, if we look carefully at Fig. 7, we can distinguish and divide data into three separate parts. In the first one, which covers the periods from August 2015 to December 2016, we can observe that the *p*-values go down after experiencing an oscillatory behavior and finally are placed in the critical region. Thus, the market moves from a relatively efficient state to an inefficient one at this period.

However, the trend changes as the market is moving toward an efficient situation, and the hallmark of this period is the volatile behavior of the market in terms of efficiency. So that after experiencing a high level of efficiency, it changes direction quickly and tends toward an inefficient situation, and again moves toward efficiency at a slower pace. This behavior is evidence for the prevailing of the AMH, which is emphasized in this study. Finally, in the third stage, it can be realized that the market efficiency is slowly and steadily following a downward trend, which can be seen in the previous results (Figs. 4, 5, and 6).

Evaluating the results based on the *GS* method

In the previous section, we examined the adaptive behavior of the study's data in terms of the adaptive market hypothesis (AMH) based on a linear method (*AQ* test). Now, this concept is evaluated by applying a nonlinear method (*GS* test). Accordingly, as before, we tried to investigate each data's behavior over time and in the form of different window lengths (50, 100, 150, and 250 days). Furthermore, the sequence of the *p*-values of the relevant test statistic, which indicates changes in the level of market efficiency, has been evaluated.

We can observe (Fig. 8) that the overall market efficiency condition improved when the window length increased. However, an exception is visible between 150 and 250 days that the null hypothesis has been rejected, amplified at a 10% significant level.

The obvious point from obtained results, which is detectable from viewing the relevant figures (Figs. 9, 10, 11, and 12), is that the spotted *p*-values of *GS* test statistics represent a fluctuating behavior. This finding is also observable

Fig. 9 Dynamic conduct of *GS* test's *p*-values in a 50-day time window

Fig. 10 Dynamic conduct of *GS* test's *p*-values in a 100-day time window

concerning the different time windows (from 50 to 250 days) and diverse rolling samples. Moreover, the most observed number for the rejection of the test statistics' null hypothesis is dedicated to the 100-day window length of the market study.

If we look carefully at Figs. 10, 11, and 12, we can find that in the early periods, we see sudden variations in the *p*-values, which indicates a reciprocal behavior in the observations. In fact, the market moves away from inefficiency, but once again slowly and steadily returns to this situation, which indicates a kind of instability in the market in terms of efficiency. In the following and most periods, we observe fluctuations in the *p*-values; however, mostly these fluctuations have occurred in areas outside the critical region, indicating efficiency in the market.

Generally, based on the obtained results (especially the swinging behavior of the *p*-values), we can infer that the market is compatible with the concept of the AMH. Consequently, market efficiency follows an adaptive manner.

Conclusion

The European Union Emission Trading Scheme (EU ETS) is the greatest emissions trading trial globally. However, there are several other mandatory schemes somewhere else; the positive result of the EU ETS would still deliver a strong momentum for creating a market-based climate change policy on the world scale. Moreover, the research in market efficiency is worthwhile for reinforcing the formation of an integrated national ETS, which reduces carbon emissions and establishes a low-carbon economy.

This study scrutinized the efficiency of the phase III EU ETS CO₂ market in an adaptive context. We utilized a rolling-sample technique with different window lengths consistent with the adaptive market hypothesis (AMH) implication to trail the time variation of efficiency. Furthermore, two alternative tests (namely automatic portmanteau (*AQ*) and generalized spectral (*GS*)) have been applied for investigating linear and nonlinear dependence. The obtained results were analyzed from two diverse aspects: firstly, we focused on

Fig. 11 Dynamic conduct of *GS* test's *p*-values in a 150-day time window

Fig. 12 Dynamic conduct of *GS* test's *p*-values in a 250-day time window

checking the market efficiency in the AMH context. Secondly, the evolving behavior on each market has been examined by shifting toward longer time windows (from 50 to 250 days). With exact consideration in all the results, we can claim that the observed behavior of CO₂ allowances prices in phase III EU ETS indicates an AMH verification and, as a result, confirms the adaptability of the market in terms of efficiency.

The other aspect of the study was to analyze the existence of evolutionary behavior on the market. Therefore, we checked the results by applying a rolling window method and four different window lengths (50, 100, 150, and 250 days) on the test statistics to achieve this goal.

In the third phase of the EU ETS scheme, we witness a movement toward a more mature form of the market. As we move away from the early years in this phase, market efficiency improves, as can be seen from the results of the *AQ* test. Some key factors have contributed to improving the market efficiency situation in phase III and achieving this maturity level. They include the deployment of a single EU-wide emissions cap on allowances, the steady phase-out of free allocation over phase III, and replacing it with auctioning as the primary method of allowance allocation; the launching of the Union registry as a centralized registry system (the single European Union Registry) to record of all allowance holdings and transactions; and finally the establishment of the Market Stability Reserve (MSR) system.

Alongside these internal factors which affect the EU ETS carbon market efficiency during this phase, some external or peripheral factors have also potentially influenced developments in the degree of market efficiency. For instance, in 2014, Eurozone economies falter again, and European economies are poised to slide into their third recession in 5 years. Also, this year, oil prices (as a contributor to carbon emission) crashed. In July 2014, the oil prices recorded over \$100 a barrel, but it plummets to just

\$60 for the rest of the year since then. The notable factors for describing this phenomenon are soaring US oil production, the coming back of Libyan oil to the market, and the OPEC disagreement on production cuts. In November 2015, the world struck a deal on climate change that is the so-called Paris climate accord, and it had a significant role in enhancing the efforts on carbon reduction around the world. In 2016, Britain votes to leave the European Union, and this decision spread uncertainty in the financial markets in the EU and across the globe which its effects still exist. The global economic growth (10 years after the Great Recession) picked up, and stock markets worldwide experienced record highs. In 2018, the USA triggered a trade war with China, which led to turmoil in global financial markets, and finally, in 2020, the COVID-19 pandemic has unleashed exceptional shocks through all facets of society, from strained healthcare systems to the closure of economies. The lockdowns in diverse countries have initiated a global economic shock at a worrying pace and carrying severe recessions for many countries as an excessive phenomenon.

In general, we can conclude that regardless of different events and challenges, which happened during phase III of EU carbon market implementation and influenced the market efficiency, and also despite the shortcomings experienced in the early years of phase III (related to the economic downturn, overlapping policies, and the consequent formation of an allowance surplus), it is expected to experience a more resilient market in phase IV by addressing the past shortcomings and reforming the system through the actions like strengthening of the MSR and improving the flexibility on the supply side.

Author contribution Majid Mirzaee Ghazani: conceptualization, investigation, methodology, formal analysis, visualization, writing the original draft; Mohammad Ali Jafari: calculation, review, editing, and made suggestions to improve the quality of the manuscript.

Data Availability The datasets used/or analyzed during the current study are available upon request.

Declarations

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Conflict of interest The authors declare no competing interests.

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