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Modeling the Nexus between European Carbon Emission Trading and Financial Market Returns: Practical Implications for Carbon Risk Reduction and Hedging

Mosab I. Tabash [1,*], Mujeeb Saif Mohsen Al-Absy [2,*] and Azzam Hannoon [3]

[1] College of Business, Al Ain University, Al Ain P.O. Box 64141, United Arab Emirates
[2] Accounting and Financial Science Department, College of Administrative and Financial Science, Gulf University, Sanad 26489, Bahrain
[3] Accounting & Finance Department, College of Business Administration (COBA), American University in the Emirates, Dubai P.O. Box 503000, United Arab Emirates; azzam.hannon@aue.ae
[*] Correspondence: mosab.tabash@aau.ac.ae (M.I.T.); dr.mujeeb.saif@gulfuniversity.edu.bh (M.S.M.A.-A.)

Abstract: The carbon–financial nexus helps firms evaluate susceptibility to carbon risk more effectively. This is the first research article to model the short- and long-run co-integrating association between European financial markets, the CBOE oil price volatility index (OVZ) and the European carbon emission trading system (EU-ETS) by using the daily returns from 1 October 2013 to 1 October 2023. We utilize co-integration test followed by the ARDL framework with an error correction mechanism (ECM). Moreover, we utilize the DCC-GARCH-*t* copula framework to estimate the hedge ratio and to select an optimal portfolio weight for carbon risk hedging. Overall, the findings suggested that EU-ETS (OVZ) has a consistent positive (negative) short-term influence on all the equity returns of Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Spain and the stock indices of the whole Eurozone. However, in the long term, EU-ETS has a positive (negative) effect on the stock returns of France and the Eurozone (Belgium and Spain). Belgian and Spanish companies could implement long-term carbon reduction policies. Belgian and Spanish firms should focus on the utilization of green energy resources and the internalization of carbon emission-free mechanical processes as this may offer a safeguard against the additional pressure arising from escalating carbon prices. Finally, an optimal portfolio weight selection strategy based upon the DCC-GARCH-*t* copula approach aims for higher hedging effectiveness (HE) than the hedge ratio strategy when adopting short-term positions in Italian and Danish equity markets to reduce the risk of long-term EU-ETS volatility.

Keywords: European carbon emission trading system (EU-ETS); European financial system; CBOE oil price volatility index; ARDL; DCC-GARCH-*t* copulas; hedge ratios; optimal portfolio weights

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1. Introduction

The reviewed literature integrates insights from Jin et al. (2020), Demiralay et al. (2022), Liu et al. (2023), and Cepni et al. (2022), providing a thorough analysis of risk dynamics and hedging instruments, particularly in relation to the role of the carbon market in hedging the stock market volatility and vice versa. For instance, Jin et al. (2020) emphasize the robustness of the green bond index as an effective hedge against carbon futures, yet methodological disparities across studies raise concerns regarding the comparability of results. Demiralay et al. (2022) recognize the challenges posed by the COVID-19 outbreak while underscoring the benefits of integrating carbon futures into stock portfolios. Liu et al. (2023) illuminate the intricate nature of external influences by revealing complex risk transmission within carbon and energy markets during global events. Cepni et al. (2022) contribute valuable insights into green assets as reliable safe havens amidst climate unpredictability. To gain a more in-depth comprehension of the identified financial market dynamics, it is imperative to consider long-term consequences, broader market interconnections, and policy implications (Jin et al. 2020; Demiralay et al. 2022; Liu et al. 2023; Cepni et al. 2022). Recent research by Dong et al. (2023) explores how various uncertainty indices moderate dynamic conditional connectivity between conventional and sustainable assets. Conversely, Hoque et al. (2023) examine the volatility shock transmission mechanism between carbon and energy futures markets using a limited dataset from 2020 to 2022. Notably, there is a gap in investigating the impact of the implied volatility of oil and European carbon emission trading markets on European financial market indices. Furthermore, it is observed that returns on European financial markets possess the capacity to mitigate volatility in the long-term European carbon emission trading market.

The mechanism for trading carbon permits has emerged as a significant component of the financial landscape, not only aimed at mitigating greenhouse gas emissions but also playing a crucial role in promoting the growth of a low-carbon economy (Chen et al. 2023). Electricity-generating plants and other carbon-intensive establishments were allowed to trade carbon permits within the European Union. The European Union Emission Trading System (EU-ETS) cap-and-trade system was designed to simultaneously lower emissions and costs for members in the carbon trading system (Tan et al. 2020; Yadav et al. 2023). Participants in the carbon tradable allowance program receive annual market-tradable allowances at the commencement of each trading cycle. These allowances undergo daily pricing and are treated as newly liquid assets (Zhao et al. 2023). Market-priced tradable allowances can be considered as the foregone cost associated with emissions. Despite the significance of emission prices and their potential connection with financial assets (Suleman et al. 2023a), this scholarly paper marks the inaugural exploration into the long-term co-integration and short-term transmission of shocks from the European carbon emission trading system (EU-ETS) and the CBOE oil price volatility index (OVZ) towards the conventional financial frameworks of European economies. A thorough comprehension of the interconnectedness among diverse facets of the financial realm, including the carbon market and the stock market, is imperative for formulating portfolio allocation strategies and instituting cross-market risk management (Suleman et al. 2023a).

We are keenly interested in exploring the associations between EU-ETS and stock markets. This is because stock markets serve as indicators of economic health and corporate well-being. The stock market is a primary indicator of a healthy economy (Tabash et al. 2024). Favorable economic conditions are expected to enhance the performance of companies, making stocks more appealing to investors due to the anticipation of increased dividends (Wen et al. 2020b). Positive economic conditions contribute to heightened energy consumption and increased carbon trading prices. The prices in carbon emissions trading are anticipated to influence the economic motivations of firms, which are subsequently reflected in stock market valuations (Brouwers et al. 2016). Consequently, the equity returns and the EU-ETS are unquestionably intertwined (Razzaq et al. 2022). Compliance with government regulations on green energy usage and carbon emission reduction obliges carbon-emitting firms to purchase carbon allowances, imposing an additional financial burden on their profitability (Razzaq et al. 2022; Sun et al. 2022), especially for companies that emit large amounts of carbon dioxide and chlorofluorocarbons (Al-Absy 2024). This, in turn, could lead to a decline in equity returns. However, many European economies that rely on green energy resources for manufacturing processes may retain unused carbon allowances and trade them in the open market to maximize revenue (Mo et al. 2021). Consequently, higher EU-ETS prices also exert a positive influence on the returns of European financial markets (Suleman et al. 2023a). This further prompts an examination of the influence of EU-ETS and OVZ on the returns of the European financial market.

Another incentive to investigate the interconnection between EU-ETS and the European financial market stems from the European carbon emission trading system's crucial role in the EU's strategy to address climate change. This trading system is a key tool for efficiently cutting greenhouse gas emissions, becoming the first meaningful carbon market in history and continuing to be the biggest (refer to Teixidó et al. 2019).[1] The restructuring of the ETS framework for the third phase (2013–2020) brought about significant changes compared to the earlier phases, namely phases 1 (2005–2007) and phase 2 (2008–2012). Phase 3 of the EU carbon emission trading mechanism replaced the previous system, which was based on national caps, with a single, EU-wide limitation on emissions. In addition, auctioning became the standard way of granting permits instead of free allocation. The reform also introduced harmonized allocation rules applicable to the allowances, expanded the inclusion of more European sectors, and allocated 0.3 billion allowances to the "New Entrants Reserve". This reserve was designated to finance the deployment of innovative renewable energy technologies. This further prompts an examination of the influence of EU-ETS and OVZ on the returns of the European equity markets during phase 3 of the European carbon trading mechanism.

Firstly, we examine the short- and long-term impact of European carbon emission trading market (EU-ETS) returns and CBOE oil price volatility index (OVZ) on the European financial market returns by applying the autoregressive distributive lag model approach by (Pesaran et al. 2001). Prior to testing the ARDL model, we also applied a distinct unit root test and co-integration framework by Johansen and Juselius (1990). More recently, Zhang and Han (2022) employed the OLS regression framework to explore the moderating influence of liquidity on carbon–financial market connectedness during the period spanning from 2013 to 2021. As a second research objective, we also employ the DCC-GARCH-t copula approach to investigate whether adopting short positions in the financial market returns of European economies leads to enhanced hedging effectiveness and risk reduction against long-term positions in the European carbon emission trading market. To achieve this objective, we apply the hedge ratio (HR) strategy and the optimal portfolio weight selection strategy (OPWSS) proposed by Kroner and Sultan (1993) and Kroner and Ng (1998), respectively. Both of these strategies are grounded in the DCC-GARCH-t copula framework. The assessment of hedging effectiveness (HE) follows the methodology outlined by Ku et al. (2007). More recently, a few other studies have also utilized a similar hedge ratio (HR) and optimal portfolio weight selection (OPWSS) approach to explore the risk reduction against oil price volatility (Antonakakis et al. 2018) and bitcoin market (Suleman et al. 2023b).

Our research paper added to the body of existing literature in the following ways:

Firstly, this research article is pioneering in its exploration of the short and long-term co-integrating influence of the European carbon emission trading market (EU-ETS) and the CBOE oil price volatility index (OVZ) on the returns of the European financial market for Belgium, Finland, France, Germany, Ireland, Italy, Netherlands, Spain, Denmark, and the entire Eurozone. Notably, the majority of the work that has already been written focuses on examining how the Chinese carbon emission pricing system affects Chinese companies' financial performance (Zhang and Han 2022; Yu et al. 2022; Chen et al. 2023; Yin et al. 2019), whereas Laskar et al. (2022) have delved into the carbon–financial market nexus within the Indian economic context. However, the phenomenon of reverse causality captured the interest of Hong et al. (2017), prompting an investigation into how the carbon emission trading mechanism responded to fluctuations in financial market returns. Some additional research, particularly in the context of developing countries in South Asia, has also shed light on the direct relationship between stock market development and carbon intensity (refer to Sharma et al. 2021). Conversely, Ofori-Sasu et al. (2023) argued that equity market performance exacerbates the adverse effects of green energy resources on the carbon emission trading system within developing economies. Therefore, Ofori-Sasu et al. (2023) explored the indirect effect of financial market performance on the carbon trading mechanism. Hence, this research article stands as the first to analyze how European financial market (EU-ETS) returns respond to shocks in the European carbon emission trading market returns and the CBOE oil price volatility index (OVZ). OVZ is commonly used in various studies as a proxy for global oil price uncertainty (Asadi et al. 2023; Zhang et al. 2023).

Modeling the EU-ETS impact on stock returns provides insights into the effectiveness of such carbon reduction policies in achieving environmental goals as well as their impact on stock market performance in a developed market context. Understanding how carbon emission trading affects stock returns helps investors make informed decisions and manage risks related to environmental policies. Our study can contribute to the understanding of how quickly and accurately financial markets incorporate information related to carbon trading and environmental regulations. This insight is valuable for assessing the overall efficiency of financial markets. This is generally because companies operating in Europe are subject to carbon emission regulations, and their financial performance may be influenced by adherence to or deviation from these regulations.

Secondly, we also computed the hedging effectiveness (HE) using both the hedge ratio strategy proposed by Kroner and Sultan (1993) and the optimal portfolio weight selection strategy outlined by Kroner and Ng (1998). Consequently, we calculated both the hedge ratios and optimal portfolio weights employing the DCC-GARCH-t copulas. Our analysis aimed to determine whether adopting a short-term positioning in one of the European financial markets yields optimal hedging effectiveness (HE) against long-term positioning in EU-ETS. Furthermore, we assessed which European financial market presents the most cost-effective option for mitigating the risk associated with long-term investment in the European carbon market. The use of both hedge ratios and optimal portfolio weight selection strategy also provides practical insights for hedge managers, indicating which strategy offers maximum risk reduction against long-term investment risk in EU-ETS. This approach aligns with the methodology proposed by Antonakakis et al. (2018).

The remaining sections of this paper are arranged as follows: In Section 2, the relationship between the EU-ETS and the financial market is explained through a theoretical framework, a review of the literature, and a discussion of earlier research on the subject. The data and methodological approach are outlined in Section 3. Section 4 constitutes the findings of this study and its practical consequences. The general result of the study is summarized in Section 5 as a conclusion.

2. Literature Review

2.1. Analyzing the Theoretical Basis for the Transmission Mechanism of Shocks between the European Union's Carbon Emission Trading and the Returns in the EU Stock Market

A potent tool for fostering economic growth, facilitating the transition to a low-carbon and environmentally sustainable landscape, fostering ecological advancements, and upholding global commitments to reduce emissions is the carbon emission trading mechanism (Bibi et al. 2021). Firstly, as an economic gauge and indicator, the stock market mirrors the developmental status of an economy. Favorable economic conditions are anticipated to impact enterprise profits, influencing share prices by generating greater expected dividends for investors (Chen et al. 2023). Furthermore, heightened economic activity resulting in higher equity market performance with an increased energy demand is likely to elevate carbon emissions (Sousa et al. 2014), consequently driving up carbon emission trading prices (Jiménez-Rodríguez 2019). European businesses are required to purchase emissions allowances (EUAs) in accordance with their yearly carbon emissions under the European Union's carbon emission trading scheme (Chun et al. 2022). Consequently, elevated prices in the carbon emission trading market would intensify pressure on the majority of European economies to adhere to governmental regulations on emission reduction (Zheng et al. 2021; Suleman et al. 2023b). This, in turn, could lead to an adverse impact of carbon trading market returns on European stock markets.

Moreover, the pricing dynamics of the stock market may reflect how carbon emission trading prices affect businesses' capital costs and economic incentives (Oestreich and Tsiakas 2015). Businesses that exceed their assigned carbon emission limitations incur fees through the carbon emission trading market. Particularly for energy-intensive industries with high carbon emissions, these costs can be significant (Mo et al. 2021). Companies grappling with heightened costs may see a reduction in profitability, thereby adversely affecting their stock prices. Investors may respond negatively to companies incurring elevated carbon-related expenses, leading to a decline in the equity prices of such firms (Alkathery and Chaudhuri 2021). In addition, companies that release greenhouse gases are vulnerable to carbon risk since future price increases for carbon permits might result from potentially disastrous climate change. Essentially, the uncertainty around the price of carbon emissions in the future is the basis of carbon risk (Weitzman 2014; Oestreich and Tsiakas 2015). Consequently, higher carbon prices contribute to a depreciative impact on European equity market returns.

Secondly, in periods of elevated fossil fuel prices, European financial markets that rely on non-conventional energy sources, such as green energy, for their production processes tend to decrease their reliance on carbon-intensive fuels. This reduction in demand for emissions allowances consequently exerts a downward influence on allowance prices (Chun et al. 2022; Batten et al. 2021). While the adoption of green energy resources by European firms is effective in reducing carbon emissions through the transition to low-carbon fuels, this practice impedes the upward movement of European carbon emission trading prices (Suleman et al. 2023a). Consequently, it contributes to a downward trend in carbon trading market returns. However, the strategic incorporation of green energy by European firms not only positions them favorably concerning carbon allowances but also aligns with the broader global trend toward sustainable and eco-friendly practices. By embracing green energy sources, European enterprises showcase a dedication to environmental responsibility, cultivating a positive image and bolstering their standing in terms of corporate social responsibility. The observed reduction in carbon emissions from companies relying on renewable energy creates a favorable position in carbon trading markets. As noted by Wen et al. (2020b), these companies operate well below their allocated carbon allowances, resulting in a surplus of allowances available for trading. This strategic move becomes especially advantageous when carbon trading prices are bullish (during periods of higher carbon prices). In such market conditions, companies with lower carbon footprints can leverage their surplus allowances through trading, contributing not only to an overall reduction in carbon emissions but also enhancing their financial performance (Mo et al. 2021). Therefore, higher carbon prices lead to a favorable influence on European equity market returns.

Furthermore, the capacity of firms relying on green energy to participate in carbon permit trading adds an extra layer to their financial gains. As highlighted by Oestreich and Tsiakas (2015), the economic advantages arising from trading carbon permits during bullish market phases can be significant. The income generated through such transactions acts as an additional source of revenue, strengthening the financial sustainability of firms dedicated to sustainable practices. Thus, the stock market returns of European companies would drop (raise) in response to a reduction (increase) in the carbon emission trading market.

2.2. Empirical Studies on the Carbon–Financial Nexus

Zhang and Han (2022) explored whether liquidity can moderate the connectivity between carbon and financial assets with the aid of the OLS regression framework in the Chinese context. The results indicated that liquidity on a particular day has the ability to predict cross-section returns significantly on the following day. Furthermore, the stock market is more strongly impacted by the carbon market. In order to achieve the planned carbon emission reductions for sustainable global growth, the European carbon trading mechanism is a contributing factor. Expanding on this premise, Hong et al. (2017) predicted movements in European carbon emission prices by incorporating commodity and financial asset prices as independent variables in a predictive regression model. The overall findings indicated that the returns of financial assets and commodities from the day prior can effectively anticipate fluctuations in the EU carbon trading mechanism.

Yu et al. (2022) explored the repercussions of carbon trading on the financial behavior of companies in China using the difference-in-difference (DID) method. Their results indicate that with the introduction of the "pilot policy," there was a decline in bank loans to businesses in the pilot regions, signaling an adverse impact of carbon trading on debt financing. Further scrutiny reveals that state-owned enterprises bear a more pronounced negative influence. In another study, Laskar et al. (2022) delved into the effects of carbon emissions intensity on the profitability of the BSE-100 (top 100 companies listed on the Bombay Stock Exchange), employing the Generalized Method of Moment approach. In general, their findings suggest that India's financial performance is negatively affected by carbon trading. As reported by Ouyang et al. (2023), carbon trading exerts an influence on China's stock returns and volatility across various timeframes and economic contexts within the nation. Consequently, its application in forecasting volatility and stock price returns holds the potential to improve predictive precision.

Equity and fixed-income markets play a role in diminishing carbon emissions and fostering increased utilization of renewable energy in developing economies. Ofori-Sasu et al. (2023) present corroborating evidence in support of the proposition that the equity market exacerbates the adverse impact of carbon emissions resulting from the utilization of renewable energy by using the GMM approach. Concurrently, the corporate bond market underscores how carbon emissions impede the utilization of renewable energy. Yin et al. (2019) reported that the air quality index and the European carbon trading mechanism directly influence China's carbon trading price. Simultaneously, the CSI energy index, the industrial index, and the HS300 exert positive indirect effects on the carbon trading market. Furthermore, the volatility of China's carbon trading price is predominantly determined by internal factors, whereas the volatility of the other economic variables under investigation is largely influenced by the industrial index and the EU carbon trading price index.

Yin et al. (2019) conducted a systematic analysis using the difference-in-differences (DID) approach to investigate the effects of environmental laws on carbon emissions on corporate stock returns. Their results show that the increased earnings of businesses trading carbon emission allowances are positively impacted by the creation of China's carbon emissions trading market. In the meantime, Sharma et al. (2021) used the CS-ARDL model to assess how the rise of the stock market, personal income, increased trade, adoption of renewable energy, and technical advancements affected the carbon intensity of four South Asian countries between 1990 and 2016. The empirical results indicated that the expansion of trade, stock market growth, and increased per capita income were associated with heightened carbon intensity in South Asian countries. Conversely, the increased adoption of renewable energy sources and advancements in technology resulted in a reduction in the carbon intensity of energy consumption.

Jin et al. (2020) scrutinized effective hedging strategies concerning carbon market risk, with a specific focus on the correlation between carbon futures returns and prominent market indices (VIX, energy, commodities, and green bonds). Of particular significance is the heightened correlation identified between the green bond index and carbon futures, particularly during intervals marked by market turbulence. The comprehensive results obtained from both static and dynamic hedge ratio models corroborate the claim that the green bond index emerges as the foremost hedge for carbon futures. This observation endures, displaying resilience even in the face of acute financial crises. Simultaneously, Demiralay et al. (2022) employed dynamic conditional correlation (DCC) models to evaluate the feasibility of employing carbon futures for hedging and diversification in stock portfolios. The overarching findings emphasize that introducing a nominal proportion of carbon futures into a stock portfolio contributes to an improvement in hedging benefits, consequently mitigating the overall risk associated with a given anticipated return. It is crucial to acknowledge, however, that the dynamics and effectiveness of carbon futures hedging are influenced by the exigencies of the COVID-19 epidemic. Despite this limitation, the strategic incorporation of carbon within a stock portfolio demonstrates a positive influence on overall performance when subjected to meticulous risk adjustments. Liu et al. (2023) engage in a nuanced analysis of the intricate dynamics of risk transmission between energy and carbon markets, situated within the framework of the increasing global financial integration. Utilizing the DCC-MVGARCH model and spillover index, the investigation unveils resilient volatility correlations and bidirectional spillover effects within the European energy and carbon emissions markets. Notably, these dynamics demonstrate variability in response to political upheavals and fluctuations in global economic stability.

Cepni et al. (2022) conducted an assessment of the hedging capabilities of precious metals and green assets in the context of climate uncertainty. The study employed distinct transition and physical climate risk metrics derived from text analysis. Notably, green bonds exhibited favorable correlations with both forms of climate risk, surpassing alternative investments such as gold. This observation implies that green bonds serve as reliable safe havens in the face of climate uncertainty, shedding light on their dual role as socially conscious investments and tools for managing portfolio risk. In a study utilizing the DCC-MIDAS-X model, Dong et al. (2023) explored the impact of climate policy uncertainty (CPU), economic policy uncertainty (EPU), and geopolitical risk (GPR) on long-term correlations between conventional/energy stocks and conventional/green bonds. The findings revealed that the influence of CPU, EPU, and GPR on stock-bond correlations varied. In high GPR conditions, both conventional and green bonds acted as safe havens; however, in scenarios characterized by high EPU and CPU, green bonds exhibited superior performance. The inclusion of green bonds in diverse portfolios was found to enhance hedging efficacy. Hoque et al. (2023) employed the TPV-VAR frequency connectedness technique to investigate the interconnectedness of returns and volatilities among carbon, climate, and energy futures. The results indicated heightened total return and volatility connectivity and spillover effects within these markets, with longer-term spillovers being less pronounced compared to short-term ones. Specifically, carbon, climate, natural gas, petrol, and coal futures emerged as net shock receptors of return and volatility spillover, while heating oil, petrol futures, and Brent crude oil functioned as transmitters.

3. Data and Methodology

3.1. Data

To evaluate the influence of the European Union Emission Trading System (EU-ETS) returns and the CBOE Oil Price Volatility Index (OVZ) on the financial markets of Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Spain, and the Eurozone, we examine daily time series data spanning from 1 October 2013 to 1 October 2023. The inclusion of a decade's worth of time series data provides a substantial dataset for analyzing both the short and long-term responses of European stock market returns to fluctuations in OVZ and EU-ETS. This approach aligns with the methodologies employed by (Bouri et al. 2020) and (Suleman et al. 2023a). For our analysis, we collect daily data for the carbon emission trading market and the Dow Jones conventional European financial market from S&P Global (https://www.spglobal.com/spdji/en/) (accessed on 5 October 2023). Concurrently, we retrieve the daily time series for the CBOE Oil Price Volatility Index (OVZ) from the Federal Reserve Economic Data website (https://fred.stlouisfed.org/, accessed on 6 October 2023). The chosen timeframe for our daily financial market data corresponds to the availability of datasets covering the maximum duration, ranging from 2013 to 2023, accessible at (https://www.spglobal.com/spdji/en/, accessed on 6 October 2023).

3.2. Methodology

Adhering to the methodology outlined by Mirza and Kanwal (2017), our initial step involved applying the co-integration technique developed by Johansen and Juselius (1990) to explore the relationship between the EU-ETS and the financial market returns of European economies. Subsequently, we employed the ARDL framework proposed by Pesaran et al. (2001). The preliminary phase of analyzing the time series data entails evaluating the stationarity properties of the utilized datasets. To assess stationarity, we employed both the tests proposed by Dickey and Fuller (1981) and Phillips and Perron (1988). These tests assist in determining whether the series used for analysis demonstrates stationarity or not.

The following equation is employed to examine the stationary characteristics of EU-ETS, OVZ, and European financial market indices.

$$\Delta y_t = \delta_0 + \theta y_{t-1} + \gamma_1 \Delta y_{t-1} + \gamma_2 \Delta y_{t-2} + \ldots\ldots\ldots\ldots\ldots \gamma_p \Delta y_{t-p} + \eta_t trend + \varepsilon_t \quad (1)$$

The variable y_t represents the series under consideration for stationarity testing, while ε_t denotes the independent and identically distributed error term. The appropriate lag length for conducting these assessments was identified through the Schwarz-Bayesian Information Criterion (SIC). Additionally, the Philips–Perron (PP) test was conducted, as the Augmented Dickey–Fuller (ADF) test loses validity in the presence of autocorrelation (Asadi et al. 2023). In Equation (1), we evaluate the null hypothesis, positing that θ equals zero, by comparing it to the one-tailed alternative proposing that θ is less than zero. If θ is established as both negative and statistically significant, the series y_t is considered to demonstrate stationarity.

3.2.1. Co-Integration Test by Johansen and Juselius (1990)

Given that we are aware of the non-stationary nature of EU-ETS and financial market returns of European economies employed in this analysis at their respective levels $I(1)$, we apply the co-integration technique presented by Johansen and Juselius (1990) to examine long-term association amongst them. Utilizing the Granger representation theorem as outlined by Engle and Granger (1987), the vector autoregressive error correction representation of y_t can be expressed as follows:

$$\Delta y_t = \pi y_{t-1} + \sum_{j=1}^{p-1} A_j \Delta y_{t-j} + \varnothing D_t + \varepsilon_t \quad (2)$$

In Equation (2), $\pi = 1 - \sum_{j=1}^{p} A_j$ and $A_j = -\sum_{i=j+1}^{p} A_i$. In this context, the matrix π symbolizes the enduring association among the EU-ETS and equity returns within the VAR framework, and the count of co-integrating relations can be deduced by examining the rank of matrix π, as outlined by Johansen and Juselius (1990). D_t represents a vector incorporating deterministic elements such as a constant and trend, while ε_t is a matrix of random errors that follow a normal Gaussian white noise process with a constant variance and zero mean. Initially, if there is no linear combination between the variables that are indicated, the rank of matrix π (represented as $r(\pi)$) is 0. Secondly, the matrix obtains full rank and becomes invertible when $r(\pi) = n$. This indicates that there is no co-integration and that all variables are stationary at their respective levels. Thirdly, the system has k linear combinations if $0 < r(\pi) = k < n$. All variables develop a pairwise long-term association with each other in the case when $k = n - 1$. Thus, using the maximum eigenvalue statistics and the trace test, the test for $r(\pi) = n$ may be carried out as follows:

$$\lambda_{trace} = -T \sum_{i=r+t}^{n} \ln\left(1 - \hat{\lambda_i}\right) \quad (3a)$$

$$\lambda_{max} = (r, r+1) = -\text{Tln}\left(1 - \hat{\lambda}_{r+n}\right) \quad (3b)$$

In this case, T is the number of applicable observations following lag correction, and λ is the computed eigenvalue derived from the projected matrix. The null hypothesis, according to which the number of co-integrating links is either less than or equal to r, is assessed using the trace statistics. The greatest eigenvalue, on the other hand, investigates the alternative hypothesis, which states that the number of co-integrating vectors is $r + 1$, rather than the null hypothesis, which states that it is exactly r. Both of these equations, i.e., Equations (3a) and (3b), rely on characteristic roots, and as the characteristic root approaches zero, the values of both λ_{max} and λ_{trace} decrease, thereby diminishing the likelihood of longer-term linkages between EU-ETS and the financial market returns of European economies.

3.2.2. ARDL Framework by Pesaran et al. (2001)

In conjunction with the Johansen–Juselius co-integration test, we also apply the ARDL bound test approach as proposed by Pesaran et al. (2001) to explore co-integration, ensuring the robustness of our estimates. Furthermore, it is noteworthy that the co-integration approach is particularly responsive to variations in small sample sizes and different lag lengths of the variables (Mirza and Kanwal 2017). The ARDL bounds testing methodology presents numerous advantages and is applicable regardless of whether the variables demonstrate $I(0)$ or $I(1)$ characteristics or a combination of both. It remains robust in situations of limited sample sizes, accommodates adjustments for lags in the model, and offers impartial estimates of the long-term model, coupled with reliable t-statistics, even when confronted with endogeneity (Suleman et al. 2022). Furthermore, a straightforward linear transformation may be used to convert the ARDL limits testing technique into a dynamic "unrestricted error correction model". This UECM efficiently combines long-term equilibrium with short-term dynamics while preserving all pertinent long-term data. For the short- and long-term effects of EU-ETS and the CBOE oil price volatility index (OVZ) on the stock indexes of European economies (EU-SI), the most basic form of the ARDL framework is as follows:

$$\Delta SI_t = \mu + \alpha_1 SI_{t-i} + \alpha_2 EU - ETS_{t-i} + \alpha_3 OVZ_{t-i} + \beta_1 \Delta SI_{t-j} + \beta_2 \Delta EU - ETS_{t-j} + \beta_3 \Delta OVZ_{t-j} + \varepsilon_t \quad (4)$$

Whereas, according to Pal and Mitra (2015) and (Suleman et al. 2022), Equation (4) can be re-written as follows:

$$\Delta SI_t = \mu + \alpha_1 ECT_{t-1} + \alpha_2 EU - ETS_{t-1} + \alpha_3 OVZ_{t-1} + \sum_{i=1}^{n1} \beta_1 \Delta SI_{t-i} + \sum_{i=0}^{n2} \beta_2 \Delta EU - ETS_{t-i} + \sum_{i=0}^{n} \beta_3 \Delta OVZ_{t-i} + \varepsilon_t \quad (5)$$

In Equation (5), SI_t as the dependent variable is represented by the stock market indices of Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Spain and the Eurozone, whereas $EU - ETS_t$ and OVZ_t represent the European carbon emission trading market indices and CBOE oil price volatility index. Co-integration is assessed through F-statistics. For instance, in Equation (5), the existence of co-integration can be evaluated by initially estimating the model using ordinary least squares. Subsequently, by constraining all calculated coefficients of past level variables to zero (see Pablo-Romero and De Jesús 2016), a test is conducted for the null hypothesis H0: $\alpha_1 = \alpha_2 = \alpha_3 = 0$, contrasting it with the alternative H1: $\alpha_1 \neq \alpha_2 \neq \alpha_3 \neq 0$ (Mirza and Kanwal 2017). Moreover, $\alpha_1 ECT_{t-1}$ (ECT − error correction term) can also be referred to s $\alpha_1 SI_{t-1}$ as the "adjustment speed" of the model returning to long-term equilibrium (Suleman et al. 2022).

Suleman et al. (2022) suggested that developing a suitable econometric model with an ideal lag structure is essential for accurate parameter identification in the suggested model. By determining the smallest values of AIC (Akaike Information Criteria) and BIC (Bayesian Information Criteria), the optimal lag structure can be determined. Following the determination of the ideal latency, the bound testing strategy recommended by Pesaran et al. (2001) may be used to assess a sustained relationship between the primary variables. Two sets of criterion standards, such as lower and upper critical limits connected to a certain significance level, were computed by Pesaran et al. (2001). When the regressors demonstrate the integration of order zero ($I(0)$), the lower critical constraint is applied, and when they demonstrate the integration of order one ($I(1)$), the upper critical constraint is applicable If the F-statistic is higher than the upper critical limit, we claim that a long-term link exists; if it is lower than the lower critical bound, we cannot reject the null hypothesis, which implies that co-integration does not exist.

3.2.3. Hedge Ratio Strategy and Optimal Portfolio Weight Selection Approach Based upon the DCC-GARCH-t Copula Approach

The rationale behind our adoption of the DCC-GARCH-t copula approach for hedge ratios is rooted in its application in recent studies, including those by (Sheikh et al. 2024), (Suleman et al. 2023a), (Akin et al. 2023), and (Hu and Borjigin 2024). Furthermore, the insignificance of the asymmetric term associated with the ADCC and EGARCH models reinforces our choice, affirming that the DCC-GARCH model yields the most reliable estimates for hedging long-term volatility in the European carbon emission trading market. Therefore, the utilization of DCC-GARCH for hedge ratios provides us with the most significant results for portfolio optimization. In addition to investigating hedge ratios, we delve into the estimation of an optimal portfolio weight selection strategy. This exploration aims to discern whether superior hedging effectiveness and greater risk reduction result from the hedge ratio strategy proposed by (Kroner and Sultan 1993) or the optimal portfolio weight selection strategy outlined by (Kroner and Ng 1998). By undertaking this comparative analysis, we seek to identify the approach that maximizes risk reduction for hedging long-term volatility in the carbon market.

In the existing scholarly literature, Antonakakis et al. (2018) employed the DCC-GARCH-t copula methodology to scrutinize the efficacy of hedging equity returns of oil firms against the enduring volatility in oil prices. Conversely, Suleman et al. (2023b) employed the DCC-GARCH-t copula method to develop a hedge ratio strategy aimed at mitigating the risk associated with maintaining a prolonged position in sustainable financial market returns. In a parallel vein, Bouri et al. (2021) calculated the overall conditional connectedness indices among crypto assets and investigated the moderating influence of investor sentiment on said indices across 15 cryptocurrencies using a quantile-on-quantile regression framework. Cepni et al. (2022) also applied the DCC-GARCH approach to explore the hedging potential of sustainable assets, specifically sustainable bond indices, against uncertainties arising from climate policies. Moreover, the DCC-GARCH-t copula approach was also utilized to hedge long-term bitcoin investors' sentiments by adopting short-term positioning in U.S. sectoral stocks. The collective findings indicated that investments in green bonds represent a viable avenue for hedging climate-related uncertainties. Furthermore, Wang et al. (2021) employed the frequency domain DCC-GARCH approach to assess the hedging potential of gold and exchange rates in response to volatility in financial market returns. The overall results indicated that gold serves as a short-term solution for hedging financial market returns, while investments in the forex market emerge as a viable option for medium and long-term horizons to hedge against equity market risks. Notably, Sheikh et al. (2024) recently utilized the DCC-GARCH-t copula methodology to formulate a hedge ratio and optimal portfolio weight selection strategy, aiming to mitigate the risk associated with adopting a prolonged position in the Australian conventional financial market through a short-term positioning in both conventional and sharia-compliant financial markets.

We adopted the methodology outlined by Kroner and Sultan (1993) and Kroner and Ng (1998) to estimate the hedge ratio strategy and the strategy for selecting optimal portfolio weights, respectively. To achieve this objective, we employed the DCC-GARCH-t copula approach. In a similar vein, Suleman et al. (2023a) explored both hedge ratio and optimal portfolio weights by using the DCC-GARCH approach, comparing their effectiveness in mitigating long-term volatility in a specific asset class by taking short-term positions (sell) in another asset class.

$$\beta_t^{EUETS-SI} = \frac{h_t^{SI-EUETS}}{h_t^{SI}} \tag{6}$$

Equation (6) explains whether short-term positioning in one of the stock markets indices (SI) of European economies provided cost-effective risk reduction and maximum hedging effectiveness (HE) against long-term carbon market volatility in the European domain. $\frac{h_t^{SI-EUETS}}{h_t^{SI}}$ is the ratio of the co-variance $\left(h_t^{SI-EUETS}\right)$ between European carbon emission trading market (EU-ETS) returns and stock market returns (SI) of either Belgium or Finland or France or Germany or Ireland or Italy or Netherlands or Spain or Denmark or Eurozone, whereas h_t^{SI} is the variance of European stock market returns.

$$w_t^{SI} = \frac{h_t^{EUETS} - h_t^{SI-EUETS}}{h_t^{SI} - 2h_t^{SI-EUETS} + h_t^{EUETS}}, \text{ with } w_t^{SI} = \begin{cases} 0 & w_t^{SI} < 1 \\ w_t^{ETS} & 0 \le w_t^{SI} \le 1 \\ 1 & w_t^{SI} > 1 \end{cases} \quad (7)$$

Equation (7) determines how much investment should be placed in the stock market indices of European economies in a USD 1 portfolio of the European carbon trading market (EU-ETS) and stock market indices (SI). Therefore, it determines how much investment in stock market indices is required in order to hedge the long-term volatility in the carbon trading market. h_t^{EUETS} and h_t^{SI} are the variance in a particular stock market index and the European carbon trading market, whereas $h_t^{SI-EUETS}$ is the co-variance between both. Furthermore, we utilize the approach of (Ku et al. 2007) to extract the hedging effectiveness (HE) in an optimal portfolio weight selection strategy and hedge ratio strategy in the following manner.

$$\text{HE} = 1 - \frac{Var_{hedged}}{Var_{unhedged}} \quad (8)$$

4. Results

4.1. Descriptive Statistics

Table 1 presents the descriptive statistics of the logarithmically transformed indices of European financial markets, European carbon emission trading system (EU-ETS) indices, and the CBOE oil price volatility index (CBOE). As illustrated in Table 1, the financial markets of Finland and Denmark demonstrate elevated average stock indices, with values of 7.18 and 7.47, respectively. This stands in contrast to their counterparts in other European economies and the broader Eurozone. In contrast, Italy's stock market records the lowest average equity market indices over the past decade, with a value of 5.23 compared to other European economies.

Table 1. The table shows the descriptive statistics of the European financial market and carbon emission trading market (EU-ETS) indices.

	Belgium	Denmark	Europe	Finland	France	Germany	Ireland	Italy	Netherlands	Spain	EU-ETS	OVZ
Mean	5.8366	7.4765	5.9497	7.1890	5.9236	6.0670	6.3924	5.3279	6.3518	5.9777	4.3799	3.5890
Median	5.8678	7.3796	5.9458	7.1661	5.9164	6.0627	6.3774	5.3399	6.3222	5.9590	4.4835	3.5936
Maximum	6.0917	8.0874	6.2024	7.5513	6.2209	6.3294	6.7825	5.5815	6.9869	6.3528	6.1069	5.7843
Minimum	5.3783	6.9399	5.5631	6.7752	5.5255	5.6241	5.9692	4.9019	5.9127	5.5302	2.8798	2.6741
Std. Dev.	0.1273	0.3004	0.1091	0.1299	0.1484	0.1193	0.1747	0.1411	0.2814	0.1563	1.0513	0.3753
Skewness	−0.7678	0.4964	0.0930	0.5856	0.1110	−0.0372	0.1838	−0.4203	0.4542	−0.0183	0.2365	0.6114
Kurtosis	3.2447	1.9114	2.8720	3.1001	2.1101	2.9343	2.3427	2.5144	2.0280	2.8760	1.5952	5.6900
Jarque–Bera	264.3690	237.3472	5.5732	151.0609	91.9672	1.0758	62.0107	103.0538	193.5064	1.8263	240.2306	954.6184
Probability	0.0000	0.0000	0.0616	0.0000	0.0000	0.5840	0.0000	0.0000	0.0000	0.4013	0.0000	0.0000
Sum	15,315.19	19,618.43	15,612.10	18,863.82	15,543.48	15,919.78	16,773.79	13,980.46	16,667.22	15,685.58	11,492.96	9417.64
Sum Sq. Dev.	42.50	236.76	31.20	44.28	57.75	37.32	80.04	52.21	207.75	64.11	2898.97	369.51
Observations	2624.00	2624.00	2624.00	2624.00	2624.00	2624.00	2624.00	2624.00	2624.00	2624.00	2624.00	2624.00
Unit root test statistics at level												
ADF	−2.9380	−2.1800	−1.9900	−1.6370	−2.6300	−1.5300	−2.1000	−1.5300	−1.4420	−1.0800	−1.2800	−3.89 ***
PP	−2.8800	−2.1000	−1.4400	−1.7600	−2.5900	−1.4090	−1.9900	−1.4870	−1.7200	−1.1000	−1.1000	−4.481 ***
Unit root test statistics at 1st Difference												
ADF	−49.93 ***	−60.276 ***	−40.82 ***	−39.726 ***	−42.76 ***	−46.64 ***	−50.28 ***	−60.10 ***	−28.76 ***	−30.27 ***	−29.635 ***	
PP	−48.108 ***	−59.726 ***	−37.10 ***	−40.192 ***	−29.108 ***	−45.12 ***	−42.18 ***	−52.10 ***	−21.10 ***	−29.102 ***	−28.3 ***	

Note: This table explains the descriptive statistics of logarithmic transformed series of European financial market indices and European carbon emission trading market indices. In order to determine the stationary characteristics of the variables, we take into account the unit root tests of the Augmented Dickey–Fuller (ADF) by (Dickey and Fuller 1981) and Phillips and Perron (PP) by (Phillips and Perron 1988), respectively. Consequently, investors in European financial markets may opt to diversify their portfolios by incorporating assets from Finland and Denmark, capitalizing on their robust stock market performance. The Asterisk signs of *** implies the rejection of null hypothesis at 1% level of significance.

Contemplating a shift away from the Italian stock market could be a prudent move to mitigate potential risks associated with its comparatively lower average equity market indices. This is primarily because the Italian financial market also exhibited a higher standard deviation value of 0.1411 when contrasted with the majority of European economies' stock markets, including those of Belgium, Finland, and Germany, as well as the standard deviation value of the entire Eurozone. However, among the economies of Europe, Denmark and the Netherlands showed greater variances from the mean in both directions (upwards and downward), which may be attributable to their largest standard deviations (SD) of 0.30 and 0.28, respectively. As a result, European investors with a higher risk tolerance might discern opportunities in Denmark and the Netherlands, considering their potential for greater returns (upside variation). It is crucial to acknowledge, however, that this potential comes with the trade-off of heightened risk (downside variation).

Remarkably, the standard deviation values of 1.05 for the EU-ETS and 0.37 for OVZ exceed the observed standard deviation value across all European financial markets. Elevated volatility in carbon markets might indicate susceptibility to shifts in environmental policies or regulations. It is imperative for investors to diligently observe and evaluate the potential repercussions of regulatory changes in these markets. The heightened volatility in the oil price volatility index implies heightened risk in the energy sector. Investors holding oil-related assets should prudently oversee and manage their portfolios, considering the potential consequences of fluctuations in oil prices. This, in turn, underscores our motivation to scrutinize the influence of EU-ETS and OVZ on European financial markets. Moreover, only the financial markets of Belgium and Finland, as well as the CBOE oil price volatility index, showed excess kurtosis. This may indicate the presence of extreme values and outliers due to the leptokurtic distribution of the data.

Figure 1 visually illustrates the returns of equity markets across European economies, while Figure 2 displays the returns in the European carbon emission trading market (EU-ETS) and the fluctuations in the CBOE oil price volatility index. In Figure 1 it is evident that all European financial markets encountered heightened upside and downside fluctuations between 2014 and 2016, during the COVID-19 era (from 2020 to the end of 2021), and after 2021. A significant factor contributing to these variations in European financial market returns from 2014 to 2016 was the severe economic challenges faced by Greece, leading to a debt crisis. In 2016, the UK conducted a referendum on its European membership, and the majority voted in favor of leaving (Brexit), causing widespread economic and political repercussions. Furthermore, the COVID-19 pandemic significantly affected the world economy and has caused extreme supply chain disruptions.

Both Figures 1 and 2 depict increased upside and downside fluctuations in European equity market returns, as well as in OVZ and EU-ETS returns, respectively, in the post-COVID-19 era (after 2021). A key contributing factor to these fluctuations is the impact of energy price variations, including those of oil and natural gas, on European economies, EU-ETS, and the oil price volatility index (Bourghelle et al. 2021). Moreover, uncertainties in the global economic conditions post COVID-19 can also contribute to the fluctuations observed in EU-ETS (Li et al. 2022) and equity returns (Yang et al. 2021). This motivates researchers to further explore the impact of EU-ETS on the European financial system, incorporating the oil price volatility index (OVZ) as a control measure. Table 1 also indicates that indices of the European carbon emission trading market and European financial markets are integrated in the same order. Specificallys, at this level, both the EU-ETS and European financial market indices display non-stationary characteristics. However, when the initial difference is taken, the mean and variance of both variables remain constant, indicating ($I(1)$) dynamics. Nonetheless, the CBOE volatility index for oil prices is stationary at level, i.e., ($I(0)$).

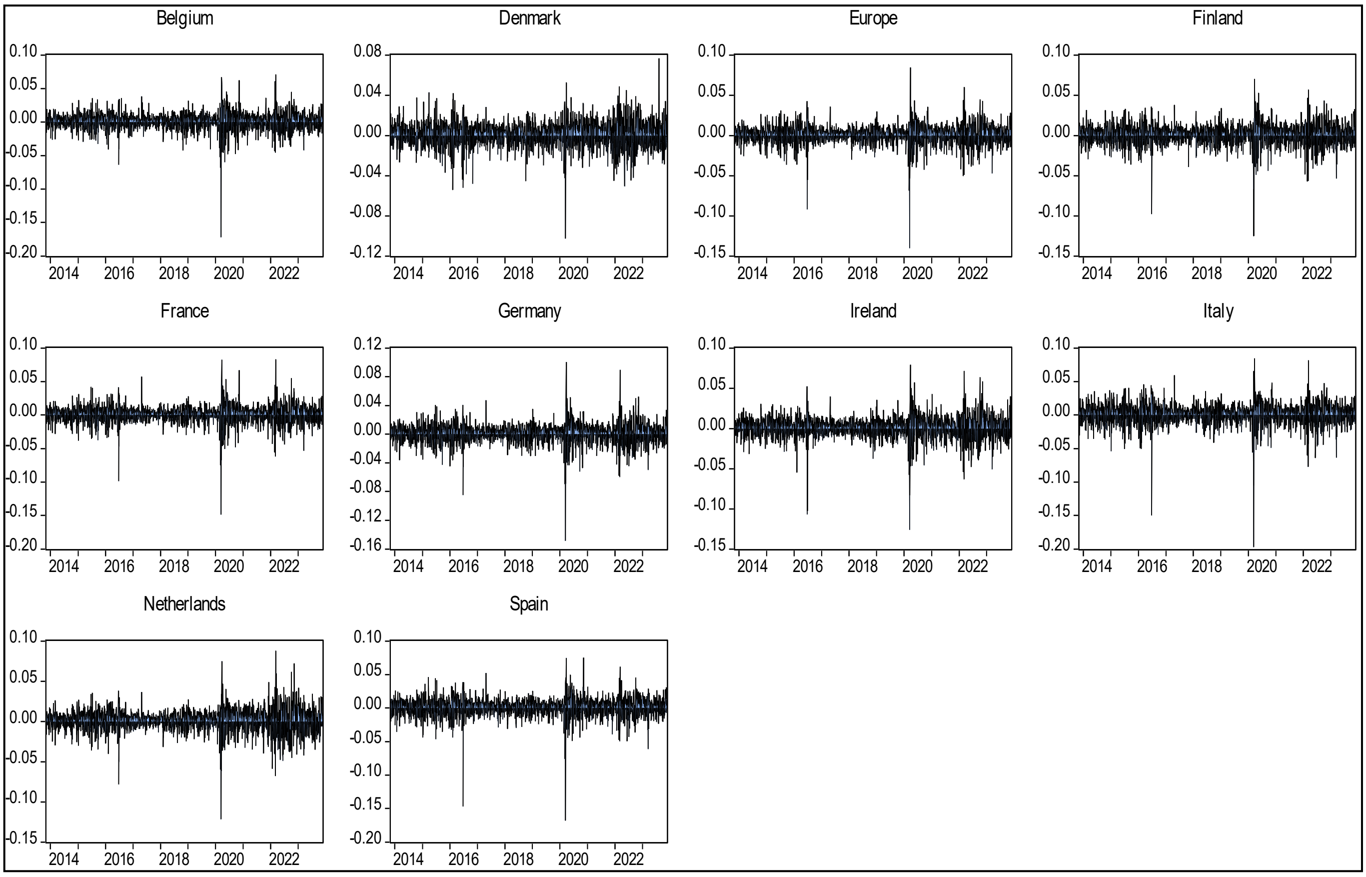

Figure 1. The figure shows a graphical representation of European financial market returns.

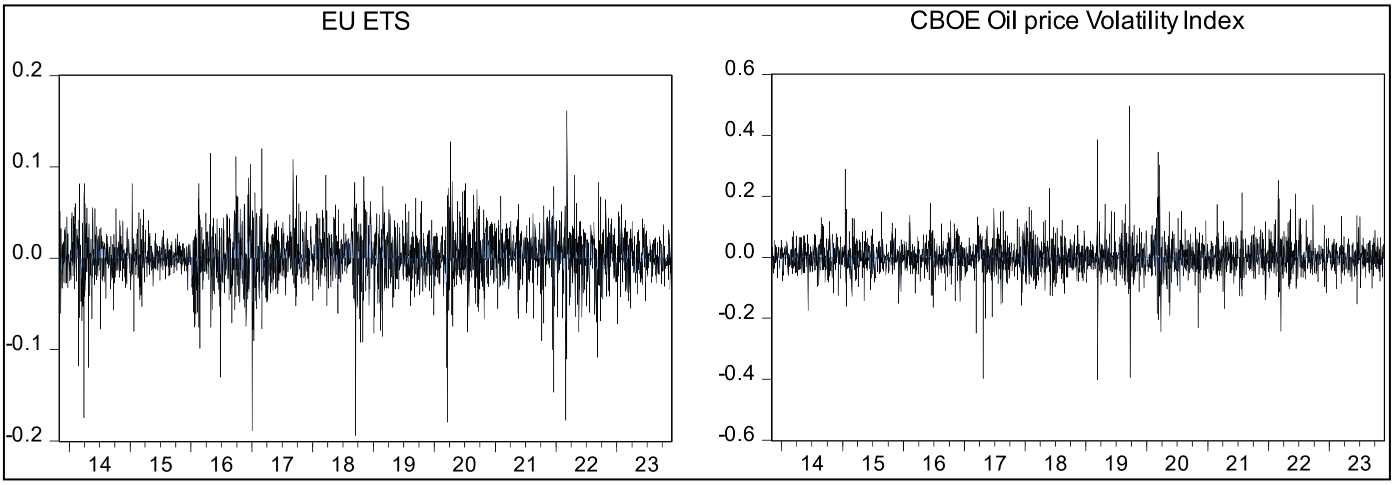

Figure 2. The figure shows a graphical representation of the CBOE oil price volatility index (OVZ) and returns in the European carbon emission trading market (EU-ETS).

In light of the aforementioned information, when dealing with variables exhibiting different orders of integration, the autoregressive distributive lag model (ARDL) approach emerges as a more practical and resilient method (Suleman et al. 2022). The stationary characteristics of returns in the EU-ETS and European financial markets are evident from Figures 1 and 2, respectively. Notably, in the literature, Mirza and Kanwal (2017) have also incorporated the Johansen and Juselius (1990) test for co-integration before employing the ARDL approach by Pesaran et al. (2001). Table 2 illustrates the results of the co-integration analysis using the Johansen and Juselius (1990) method, aiming to identify long-run co-integrating relationships between EU-ETS returns and financial market returns for Belgium, Finland, France, Germany, Ireland, Italy, Netherlands, Spain, Denmark, and the entire Eurozone. The findings in Table 2 indicate the presence of long-term co-integration between the variables, justifying the use of the ARDL approach to explore both the short- and long-term impacts of EU-ETS returns on the financial market returns of respective EU economies.

Table 2. The table shows the co-integration test of Johansen and Juselius (1990).

	Hypothesized No. of Co-Integrating Equations (CE)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob. **
ln(EU-ETS) and ln(Belgium)	None ***	0.0078	21.25	15.4947	0.0060
ln(EU-ETS) and ln(Finland)	None ***	0.0072	20.17	15.4947	0.0091
ln(EU-ETS) and ln(France)	None **	0.0067	18.078	15.4947	0.020
ln(EU-ETS) and ln(Germany)	None **	0.0075	20.25	15.4947	0.0089
ln(EU-ETS) and ln(Ireland)	None **	0.0048	14.70	15.4947	0.0365
ln(EU-ETS) and ln(Italy)	None *	0.0051	13.90	15.4947	0.0858
ln(EU-ETS) and ln(Spain)	None *	0.0047	12.71	15.4947	0.0967
ln(EU-ETS) and ln(Netherlands)	None **	0.0058	16.029	15.4947	0.049
ln(EU-ETS) and ln(Denmark)	None *	0.0051	12.473	15.4947	0.091
ln (EU-ETS) and ln(Europe)	None ***	0.0070	18.989	15.4947	0.0001

Note: This table explains the results of co-integration between the natural logarithmically transformed return series of European financial market indices and European carbon emission trading market indices by using the framework of (Johansen and Juselius 1990) The asterisks sign, i.e., ***, ** and * denoted the rejection of null of no long run co-integration because of lower p values (these p values are based upon (MacKinnon et al. 1999) p-values) at 1%, 5%, and 10% levels of significance.

4.2. ARDL Approach and Practical Implications for Long-Term Shareholders and Short-Term Speculators

Table 3 displays the estimates derived from the ARDL approach proposed by Pesaran et al. (2001). These estimates aim to assess the short- and long-term reactions of European financial market returns to the fluctuations in both the European carbon emission trading market (EU-ETS) returns and the CBOE oil price volatility index (OVZ). Additionally, as part of residual diagnostics, we provide the results of the Breusch–Pagan heteroscedasticity test (Breusch and Pagan 1979), the Durbin–Watson (DW) test for autocorrelation (Durbin and Watson 1951), and the RESET test for model misspecification, ensuring the correct functional form of variables Ramsey (1969).

Table 3. The table shows the impact of EU-ETS and OVZ on the financial markets of the European Union.

	Belgium		Finland		France		Germany		Ireland	
	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic
Long-run coefficients:										
ECT(−1))	−0.0103 ***	−4.1619	−0.0074 ***	−3.1208	−0.0102 ***	−3.6108	−0.0132 ***	−5.4193	−0.0057 **	−2.7662
ln(EU-ETS)	−0.1022 ***	−4.7408	0.0347	1.1480	0.0905 ***	4.2391	−0.0150	−0.5784	0.0959 **	2.3700
ln(OVZ)	−0.1243	−1.4936	−0.1188	−1.0161	−0.1924 **	−2.2799	−0.2218 **	−2.1834	−0.0366	−0.2249
ln(EU-ETS(-1))	−0.0011 ***	−3.4788	0.0003	0.9964	0.0009 **	2.6638	−0.0001	−0.5902	0.0005	1.6926
ln(OVZ(-1))	−0.0013	−1.3645	−0.0009	−0.9119	−0.0020 *	−1.8848	−0.0020 *	−1.7813	−0.0002	−0.2196
Short-run coefficients:										
Δln(EU-ETS)	0.0829 ***	10.4398	0.0881 ***	11.1509	0.0965 ***	12.1096	0.0950 ***	11.5877	0.0902 ***	10.8929
Δln (EU-ETS(-1))	0.0115	1.4453	0.0186 **	2.3535	0.0202 **	2.4694	0.0193 **	2.2944	0.0246 ***	2.9007
Δln (OVZ)	−0.0579 ***	−13.5311	−0.0662 ***	−15.5725	−0.0689 ***	−16.0029	−0.0701 ***	−15.8109	−0.0683 ***	−15.2685
Δln (OVZ(-1))	−0.0308 ***	−7.1052	−0.0305 ***	−7.1012	−0.0294 ***	−6.4097	−0.0285 ***	−6.0420	−0.0242 ***	−5.1185
K-statistics	4.72 ***		2.8700		3.99 **		4.732 **		2.1900	
BP heteroscedasticity	−1.0230		−1.0910		1.5400		1.4620		1.2500	
Durbin–Watson Autocorrelation test	2.1000		1.9900		2.0800		2.2000		1.9870	
Ramsey Reset test:	0.9927		0.9880		1.6500		1.0430		1.2200	
Cusum test	Stable		Stable		Stable		Stable		Stable	

Table 3. *Cont.*

	Italy Coefficient	t-Statistic	Netherlands Coefficient	t-Statistic	Spain Coefficient	t-Statistic	Denmark Coefficient	t-Statistic	Europe Coefficient	t-Statistic
Long-run coefficients:										
ECT(-1))	−0.0063 ***	−2.7202	−0.0029	−1.4550	−0.0693 ***	−3.3662	−0.0027	−1.5122	−0.0934 ***	−3.4707
ln(EU-ETS)	0.0767	1.2350	0.1673 **	1.8848	−0.1013 ***	−3.0044	0.0007	1.3842	0.0398 **	2.0859
ln(OVZ)	−5.5330	−1.5239	−0.2081	−0.6632	−0.2713 **	−2.0159	0.0005	0.5702	−0.1941 **	−2.3283
ln(EU-ETS(-1))	0.0005	1.1112	0.0005	0.9624	−0.0007 **	−2.2996			0.0004	1.5689
ln(OVZ(-1))	−0.0350	−1.3345	−0.0006	−0.6026	−0.0019 *	−1.8425			−0.0018 **	−1.9948
Short-run coefficients:										
Δln (EU-ETS)	0.0797 ***	7.8235	0.0843 ***	10.1041	0.0932 ***	10.9104	0.0460 ***	5.7824	0.0832 ***	11.5884
Δln (EU-ETS(-1))	0.0176 *	1.7134	0.0089	1.0543	0.0098	1.1200	0.0372	1.692	0.0154 **	2.0916
Δln (OVZ)	−1.7936 ***	−16.0636	−0.0657 ***	−14.5908	−0.0697 ***	−15.1067	−0.0504 ***	−11.8011	−0.0620 ***	−16.0623
Δln (OVZ(-1))	−0.7023 ***	−5.9744	−0.0260 ***	−5.4737	−0.0281 ***	−5.7513	−0.0285 ***	−6.4293	−0.0261 ***	−6.3580
K-statistics	1.8950		0.8200		3.98 **		0.9900		4.32 ***	
BP heteroscedasticity	1.2900		0.9900		1.6200		1.2200		1.1000	
Durbin–Watson Autocorrelation test	2.1100		1.9620		2.2000		1.9800		2.2300	
Ramsey Reset test:	1.0635		1.2000		1.6600		1.7400		1.6900	
Cusum test	Stable		Stable		Stable		Unstable		Stable	

Note: This table elucidates the estimated outcomes derived from the autoregressive distributive lag (ARDL) methodology proposed by Pesaran et al. (2001). To address issues relating to heteroscedasticity, autocorrelation, and model misspecification, we employed the Breusch–Pagan (BP) heteroscedasticity test, Durbin–Watson (DW) autocorrelation test, and Ramsey Reset (RR) test, respectively. The presence of asterisks (***, **, and *) signifies the rejection of the null hypothesis at significance levels of 1%, 5%, and 10%, respectively.

Moreover, Figure 3 presents a graphical representation of the Cumulative Sum Test (CUSUM) test for ARDL model stability.

Table 3 shows that long-term co-integration is established between European carbon emission trading market (EU-ETS) returns, the CBOE oil price volatility index, and financial market returns of Belgium, France, Germany, Spain, and the whole of Europe. This is generally due to the higher K-statistics values compared to the lower and upper bound critical values and negative and statistically significant values of error correction terms (ECTs). Error correction terms determine whether a model is correcting its long-term disequilibrium at a particular speed of adjustment and signify a long-term co-integrating association between the variables. According to Table 3, EU-ETS has an adverse long-term effect of 10.22% and 10.13% on the financial market returns of Belgium and Spain, whereas EU-ETS has a significant positive long-run effect of 9% and 3.98% on the financial market returns of France and the whole of the Eurozone. However, in the case of Finland, Ireland, Italy, the Netherlands, and Denmark, long-term co-integration cannot be established. In contrast to the effect of EU-ETS on European financial market returns, the CBOE oil price volatility index has a consistent long-term adverse effect of 19.2%, 22.18%, 27.13%, and 19.41% on the financial market returns of France, Germany, Spain, and the Eurozone. These results diverge from prior research, as earlier studies primarily center on examining the impact of the Chinese carbon emission trading system on the financial performance of Chinese sectors (Zhang and Han 2022; Yu et al. 2022; Chen et al. 2023; Yin et al. 2019). However, Sun et al. (2022) reported a weak association between Chinese carbon trading market returns and energy-related firms.

One rationale for the negative long-term impact of the EU Emission Trading System (EU-ETS) on the financial market returns of Belgium and Spain lies in the perception that the carbon emission trading mechanism functions as a potent driver for economic development (Bibi et al. 2021). In the context of Belgium and Spain, the stock markets reflect the status of economic development. Additionally, increased economic activity and positive equity market performance may lead to a surge in energy demand, potentially elevating carbon emissions (Sousa et al. 2014). This, in turn, could drive up prices in the carbon emission trading market (Jiménez-Rodríguez 2019). Consequently, the heightened prices in the carbon emission trading market may exert increased pressure on the financial systems of Belgium and Spain to comply with governmental regulations on emission reduction (Zheng et al. 2021; Suleman et al. 2023b). Such compliance pressures could, in the end, result in an adverse impact on carbon trading market returns in European stock markets. Another contributing factor is that prices in the carbon emission trading market have the potential to influence the economic incentives and capital costs of businesses, as elucidated by Oestreich and Tsiakas (2015). These effects may subsequently manifest in the pricing dynamics of the stock markets of Belgium and Spain.

Figure 3. Cumulative Sum Test for Parameter Stability (CUSUM) graphs for the impact of EU-ETS and OVZ on European financial market returns.

In addition to the aforementioned reasons explaining the negative long-term impacts of the EU Emission Trading System (EU-ETS) on financial market returns, it is noteworthy that the financial markets of the Eurozone region and France exhibited a favorable response to increased EU-ETS returns. This positive reaction is primarily attributed to the substantial positive long-term effects of 9% and 3.98% on the financial market returns of France and the entire Eurozone, respectively. One rationale for this positive outcome is that European companies often operate well below their assigned carbon allowances, resulting in excess allowances available for trading. This strategic approach proves particularly advantageous when carbon trading prices are on an upward trend, such as during periods of higher carbon prices (Wen et al. 2020a; Zheng et al. 2021). In market environments of this nature, businesses with lower carbon footprints have the opportunity to capitalize on their excess allowances through trading. This not only contributes to an overall decrease in carbon emissions but also improves their financial performance (Suleman et al. 2023b). Consequently, higher carbon prices result in a favorable impact on the returns of the French stock market. Additionally, the ability of companies relying on green energy to engage in carbon permit trading introduces an additional dimension to their financial benefits. As underscored by Oestreich and Tsiakas (2015), the economic advantages derived from trading carbon permits during bullish market phases can be substantial.

Our findings offer several practical implications for long-term shareholders. Firstly, businesses operating within Spain and Belgium may explore long-term sustainable practices aligned with environmental goals while also considering the financial consequences of EU-ETS on their operations. Consequently, incorporating the influence of carbon trading prices on stock returns in these markets is imperative for a comprehensive long-term investment strategy. Measures should be considered to alleviate the negative impact on stock returns without compromising environmental objectives. For instance, Belgian and Spanish companies could implement long-term carbon reduction policies by transitioning their manufacturing and production processes from carbon-intensive resources to green energy resources (Wen et al. 2020a). Hence, the utilization of green energy resources and the internalization of carbon emission-free mechanical processes may offer a safeguard against the additional pressure arising from escalating carbon prices (Oestreich and Tsiakas 2015), and it will enhance stock market performance in Spain and Belgium.

Secondly, in the long term, the financial markets in France and the entire Eurozone demonstrated a positive response to the increase in carbon trading prices. As a result, long-term investors from Belgium and Spain may identify investment opportunities in companies operating within France and the Eurozone that align with or benefit from the favorable impact of rising carbon trading prices on financial markets. Shareholders in France might contemplate adjusting their long-term investment plans based on the observed positive response in the equity market to EU-ETS, potentially reallocating resources to regions or industries showing growth linked to carbon trading. Long-term investors in France, Belgium, and Spain should be mindful of how government policies and regulations concerning carbon emissions and trading can influence financial markets. Changes in regulatory frameworks have the potential to impact investment strategies.

Thirdly, in the case of Finland, Ireland, Italy, Netherlands, and Denmark, the long-term co-integration between EU-ETS and the financial markets of these economies cannot be established, and there is no significant EU-ETS effect on the financial markets. Investors should conduct thorough country-specific analyses, recognizing that the dynamics of carbon trading impacts differ across regions. Strategies should be tailored to the unique characteristics of each market. Companies in these regions may allocate resources and efforts toward areas with more significant financial implications rather than prioritizing carbon trading price considerations in their long-term business plans.

Fourthly, the CBOE oil price volatility index also has an adverse effect on the financial market returns of France, Germany, Spain, and aggregated Eurozone equity market returns. In the long run, a 1% increase in OVZ causes the equity market returns of France, Germany, Spain, and the aggregated Eurozone to depreciate by 19.25%, 22.18%, 27.13%, and 19.41%, respectively. Due to the fact that businesses and investors in these economies may be heavily exposed to either the equity or oil market, understanding this negative correlation is crucial for risk control. Hedging strategies can be employed to offset potential losses in one market with gains in the other. Energy companies, especially in France, Germany, and Spain, may experience a long-term inverse relationship between their stock prices and oil prices. Lower oil prices might benefit consumers and oil-independent industries but could negatively affect the profitability of energy-dependent companies (see Hadhri 2021).

Table 3 also shows that the short-term positive (adverse) impact of the European carbon emission trading market (CBOE oil price volatility index) is more pronounced and consistent for all financial market returns in Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Spain, and the Eurozone. Based on these findings, we also intend to explore a few useful ramifications for short-term traders.

Initially, European corporations can utilize these results to inform short-term strategic choices concerning their environmental practices. Firms witnessing short-term positive stock price responses to returns in the carbon emission trading market may find motivation to embrace eco-friendly policies, given the potential positive impact on their stock performance. Subsequently, this illustrates that a favorable influence on stock prices could prompt governments and regulatory bodies to formulate and enforce more resilient and market-friendly mechanisms for carbon trading. Thirdly, the positive interconnection between markets has the potential to enhance overall market efficiency. The rapid transmission of information and news from one market to another reduces the probability of price disparities and accelerates the speed at which markets incorporate pertinent information. Fourthly, if the EU-ETS market undergoes a positive trend, it could initiate a feedback loop where investors in the equity market respond positively to this trend. Recognizing these behavioral aspects becomes crucial for participants in the market. Lastly, fluctuations in oil prices may hold implications for economic growth, inflation, and consumer spending. Short-term investor sentiment can be influenced by movements in both markets. For instance, a downturn in the equity market might trigger heightened demand for secure assets such as oil, and vice versa. Furthermore, traders and short-term European investors might devise strategies capitalizing on the inverse correlation between equity and oil markets. During periods of equity market downturns, opportunities to profit from potential increases in oil prices may arise.

4.3. Hedge Ratio and Optimal Portfolio Weight Selection Strategy through DCC-GARCH-t Copula Approach

Table 4a,b elucidate the effectiveness of hedging by adopting a short-term positioning in one of the European financial markets to mitigate the risk of long-term volatility in the European carbon emission trading market (EU-ETS). In Table 4a, the majority of hedge ratios are statistically significant, while most of the estimated optimal portfolio weights are statistically insignificant. Nevertheless, the optimal portfolio weight selection strategy yields higher hedging effectiveness (HE), reaching 75% and 84%, for mitigating long-term volatility in EU-ETS through short-term positioning in Italy and Denmark, respectively. This implies that for a bivariate portfolio of USD 1 comprising both EU-ETS and stocks, a greater risk reduction of 75% and 84% can be achieved by investing USD 0.25 and USD 0.16 in the Italian and Danish financial markets, respectively. Thus, the optimal portfolio weight selection strategy aims for higher hedging effectiveness (HE) when adopting short-term positions in either the Italian or Danish equity markets to reduce the risk of long-term EU-ETS volatility compared to hedge ratios.

Conversely, the hedge ratio strategy indicates that short-term positioning in Danish and Italian equity markets offers the most cost-effective risk reduction against long-term volatility in EU-ETS, requiring only USD 0.29 and USD 0.40 of investments in Denmark and Italy's financial markets, respectively, to hedge the long-term volatility of EU-ETS. However, hedging effectiveness achieved through the hedge ratio strategy is comparatively lower, providing only a risk reduction of 1% and 4% for hedging EU-ETS long-term volatility through short-term positioning in the Danish and Italian financial markets. Moreover, EU-ETS long-term volatility should not be hedged through the adoption of short-term positioning in France, as it provides the greatest expense risk reduction against long-term investment risk in EU-ETS.

Table 4. a: Hedging effectiveness through hedge ratios based on DCC-GARCH-t copula approach. b: Hedging effectiveness through optimal portfolio weight selection strategy (OPWSS) using the DCC-GARCH-t copula approach.

a.					
	Hedge Ratios	**Std. Dev.**	**5%**	**HE**	***p*-Value**
EU-ETS/Belgium	0.490	0.00280	0.490	4.00%	0.0000
EU-ETS/Finland	0.510	0.00190	0.510	5.00%	0.0000
EU-ETS/France	0.540	0.00637	0.540	6.00%	0.0000
EU-ETS/Germany	0.510	0.00558	0.510	5.00%	0.0000
EU-ETS/Ireland	0.480	0.00180	0.480	5.00%	0.0000
EU-ETS/Italy	0.400	0.00380	0.400	4.00%	0.0000
EU-ETS/Netherlands	0.460	0.00730	0.460	4.00%	0.0000
EU-ETS/Spain	0.470	0.00520	0.470	5.00%	0.0000
EU-ETS/Denmark	0.290	0.00630	0.290	1.00%	0.0000
EU-ETS/Europe	0.600	0.00010	0.600	6.00%	0.0000

b.					
Short/Long	**Optimal Portfolio Weights**	**Std. Dev.**	**5%**	**HE**	***p*-Value**
EU-ETS/Belgium	0.090	0.00387	0.090	82.0%	0.210
EU-ETS/Finland	0.090	0.00637	0.090	82.0%	0.240
EU-ETS/France	0.090	0.00190	0.090	81.0%	0.280
EU-ETS/Germany	0.100	0.00074	0.100	81.0%	0.200
EU-ETS/Ireland	0.110	0.00018	0.110	81.0%	0.150
EU-ETS/Italy	0.150	0.00740	0.150	75.0%	0.010
EU-ETS/Netherlands	0.110	0.00870	0.110	81.0%	0.120
EU-ETS/Spain	0.110	0.00000	0.110	79.0%	0.120
EU-ETS/Denmark	0.120	0.00054	0.120	84.0%	0.030
EU-ETS/Europe	0.060	0.00054	0.060	85.0%	0.500

Note: a: This table explains hedging effectiveness (HE) through the adoption of short-term positioning in European financial markets for hedging the long-term volatility in European carbon emission trading markets based upon the hedge ratio strategy of (Kroner and Sultan 1993), whereas hedging effectiveness is estimated by following the approach of (Ku et al. 2007). We utilize the DCC-GARCH-*t* copula approach to estimate the hedge ratios. b: This table explains hedging effectiveness (HE) through the optimal portfolio weight selection strategy of (Kroner and Ng 1998), whereas the hedging effectiveness is estimated by following the approach of (Ku et al. 2007). Optimal portfolio weights determine how much weightage of investment should be placed in European financial market stocks in order to obtain long-term positioning in EU-ETS in a USD 1 bivariate investment portfolio of EU-ETS and stocks (see Antonakakis et al. 2018). We utilize the DCC-GARCH-*t* copula approach to estimate the optimal portfolio weights.

4.4. Robustness Analysis

We adopted a rigorous approach to re-evaluate co-integration analysis, addressing the potential impact of structural breaks on our findings. Initially, we incorporated dummy variables into the co-integration analysis to account for these structural breaks. This methodology was crucial for capturing and mitigating the effects of any sudden shifts or changes in the underlying data. To further enhance the robustness of our analysis, we integrated the methodological framework proposed by Franses and Lucas (1998). This framework is specifically designed to estimate co-integration in the presence of outliers, providing a more comprehensive understanding of the relationships within the data. It can be contended that the methodology resilient to outliers is nearly synonymous with conventional Gaussian-based analysis, incorporating supplementary dummy variables (Franses and Lucas 1998).

Building on the work of Johansen and Juselius (1990), we extended our analysis to include considerations for structural breaks. We employed the Zivot and Andrews (1992) unit root test to identify these breaks in the time series data. Once identified, dummy variables were introduced to analyze co-integration in the presence of structural breaks, following the approach outlined by Søren Johansen et al. (2000). Figure 4 visually illustrates the presence of structural breaks in both the carbon emission trading market and European financial markets. Meanwhile, Table 5a details the specific dates of these structural breaks in the time series data, providing a clear understanding of when significant shifts occurred. With the precise identification of structural break points, we proceeded to re-estimate the Johansen and Juselius (1990) test for co-integration. This step was essential to ensure the robustness of our findings and account for any changes in the underlying dynamics of the markets. The results of our analysis are presented in Table 5b, which explicitly outlines the co-integration analysis in the presence of structural breaks. Notably, Table 5b demonstrates that long-term co-integration persists even in the presence of structural breaks. This finding is pivotal for understanding the enduring relationships between variables in the European carbon emission trading and financial markets despite the occurrence of significant structural breaks. Overall, our meticulous approach strengthens the reliability and validity of the co-integration analysis in the context of dynamic and changing market conditions.

Table 5. The table shows a: structural break dates; b: co-integration analysis in the presence of structural breaks.

a.

Variable	Structural Break Date
Belgium stock market indices	13 March 2018
Denmark stock market indices	24 March 2020
European as a whole stock indices	11 February 2020
Finland stock market indices	30 October 2020
France stock market indices	2 November 2020
Germany stock market indices	2 November 2020
Ireland stock market indices	11 February 2022
Italy stock market indices	29 November 2016
Netherlands stock market indices	2 November 2020
Spain stock market indices	5 December 2016
European carbon trading market indices	2 February 2021

b.

Hypothesized No. of CE(s)	Trace Statistic	0.05 Critical Value	Prob. **
Belgium-EUETS Null: No co-integration	16.44 **	15.49471	0.0359
Denmark-EUETS Null: No co-integration	16.765 **	15.49471	0.041
Europe-EUETS Null: No co-integration	16.18 **	15.49471	0.00781
Finland-EUETS Null: No co-integration	15.62 **	15.49471	0.0372
France-EUETS Null: No co-integration	17.34 **	14.2646	0.0285
Germany-EUETS Null: No co-integration	18.68 **	14.2646	0.0176
Ireland-EUETS Null: No co-integration	17.34 **	14.2646	0.0285
Italy-EUETS Null: No co-integration	18.81 **	14.2646	0.03023
Netherlands-EUETS Null: No co-integration	19.35 ***	14.2646	0.00692
Spain-EUETS Null: No co-integration	16.833 **	14.2646	0.0109

Note: a: Structural break point dates in the time series data of the European carbon emission trading market and European financial markets. b: Co-integration analysis in the presence of structural breaks. The asterisks sign of *** and ** implies the rejection of the null hypothesis of no long-run co-integration in the presence of structural break points at 1%, and 5% levels of significance.

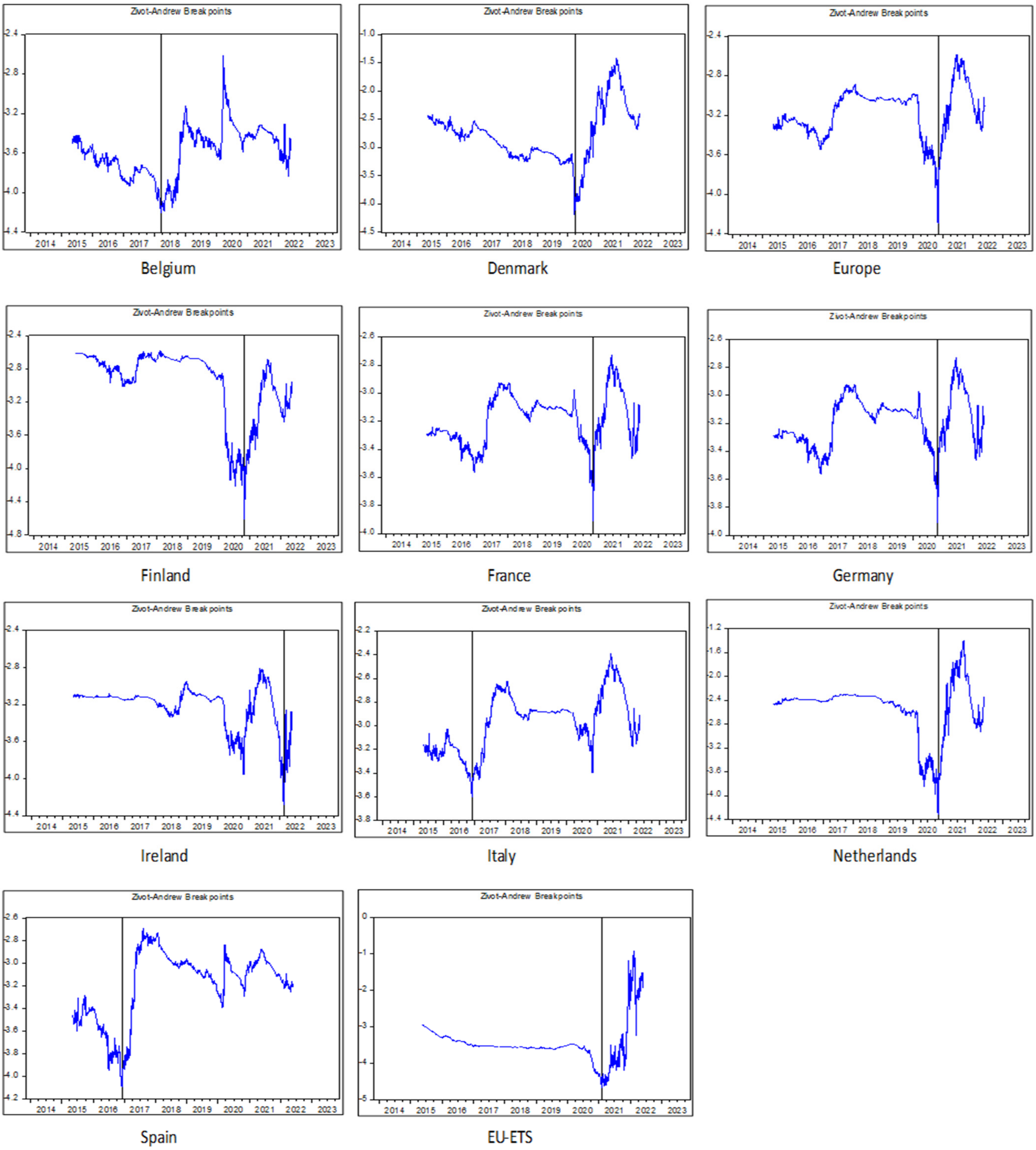

Figure 4. The figure shows the Zivot Andrew Unit root test with structural breaks.

Conventional tests like co-integration and unit root exhibit sensitivity to anomalous occurrences like anomalies and structural disruptions. To examine the impact of these occurrences, we employ the outlier-robust co-integration approach by (Franses and Lucas 1998). When traditional co-integration findings may be influenced by a few anomalous observations, our outlier-robust co-integration test offers a novel diagnostic tool for indicating this possibility. The fact that the suggested robust estimator may be used to determine weights for each observation is a key component of our methodology. Therefore, it may be utilized to determine the general dates of atypical occurrences. Additionally, Bohn Nielsen (2004) verified the findings of Franses and Lucas (1998).

In order to implement the outlier robust co-integration analysis, Franses and Lucas (1998) considered the standard vector auto-regression process as follows:

$$\Delta y_t = \alpha\beta' y_{t-1} + \phi_1 \Delta y_{t-1} + \ldots\ldots\ldots\phi_{p-1}\Delta y_{t-p+1} + \mu + \varepsilon_t \quad (9)$$

In order to mitigate the impact of outliers, Lucas (1997) introduced a Johansen-type testing methodology that relies on non-Gaussian pseudo-likelihoods. The specific instantiation of this approach in the present study is outlined as follows: the parameters in Equation (9) are estimated by employing Student-t pseudo-likelihood with v degrees of freedom.

$$\mathcal{L}(\theta) = \prod_{t=1}^{T} \frac{\Gamma\left(\frac{v+k}{2}\right)}{\Gamma\left(\frac{v}{2}\right)|\pi v V|^{\frac{1}{2}}} \left(1 + \frac{\varepsilon'_t V^{-1} \varepsilon_t}{v}\right)^{-(v+k)/2} \quad (10)$$

It is essential to highlight that the vector of unknown parameters is denoted as θ. It is crucial to emphasize that the likelihood mentioned in Equation (10) is employed as a pseudo-likelihood, following the conceptual framework introduced by Gourieroux et al. (1984). It is important to note that in this approach, the distribution of the error term, denoted as ε_t, is not constrained to be Student-t distributed. Rather, it is only required to satisfy specific weak conditions, as elucidated by Lucas (1997). The adoption of the Student-t pseudo-likelihood in Equation (10) serves as a method to address the impact of anomalous data structures on the inference of unit roots. The co-integration test, formulated on the basis of the Student-t pseudo-likelihood, is constructed in the following manner:

$$2ln\left(\frac{\mathcal{L}(\hat{\theta})}{\mathcal{L}\left(\tilde{\theta}\right)}\right) \quad (11)$$

Equation (11) relies on a test involving a ratio of two pseudo-likelihoods, which we refer to as a pseudo-likelihood ratio (PLR) test. The weights for the individual observations are obtained as follows:

$$y_t = u + \varepsilon_t \quad (12)$$

when the disturbances (represented as ε_t) exhibit independence and identical distribution (iid) characteristics, each having a zero mean and unit variance, the Student-t maximum pseudo-likelihood (MPL) estimator is employed to address this scenario as follows:

$$\sum_{t=1}^{T} \frac{(v+1)}{v} \cdot \frac{(y_t - u)}{1 + (y_t - u)^2/2} = 0 \quad (13)$$

In relation to parameter u, let $\hat{u}$ represent the ultimate estimate. Subsequently, $\hat{u}$ can be construed as the arithmetic mean of the reweighted sample $w_t^2 y_t$.

$$w_t^2 = \left(1 + (y_t - \hat{u})^2/v\right)^{-1} \times \left(T^{-1}\sum_{t=1}^{T} \left(1 + (y_t - \hat{u})^2/v\right)^{-1}\right)^{-1} \quad (14)$$

This derivation stems from the equivalence of the expression of $\hat{u} = T^{-1}\sum_{t=1}^{T} w_t^2 y_t$ is the same as $\sum_{t=1}^{T}\left(w_t^2 y_t - w_t^2 \hat{u}\right)$, as readily observed to adhere to condition (13). It is noteworthy that the upper bound of $\left(w_t^2\right)$ is not confined to 1 but is rather constrained by $(v+1)/v$. Additionally, parameter $\hat{u}$ can be construed as the estimator for u in the weighted regression model through the ordinary least squares (OLS) methodology.

$$w_t y_t = w_t u + w_t \varepsilon_t \quad (15)$$

The parameter w_t may be construed as the weight assigned to the observation at time i. A diminished value of w_t signifies that the observation diverges from the overall model pattern. Conversely, an alternative interpretation of w_t involves considering it as the reciprocal of the standard deviation of the error term. In a manner analogous to the Student-t Maximum Penalized Likelihood (MPL) estimator applied to Equation (12), the Student-t MPL estimator for Equation (9) may be conceptualized as the Gaussian MPL estimator applied to a weighted iteration of Model (1). The assigned weights are determined as follows:

$$w_t = \left(\frac{v+k}{v+\varepsilon'_t V^{-1}\varepsilon_t}\right)^{1/2} \tag{16}$$

Figure 5 shows the weights of the observations associated with the conventional European financial market and carbon emission trading market indices, whereas Table 6 shows that co-integration between the carbon emission trading market and conventional financial market returns when utilizing the outlier robust framework of (Franses and Lucas 1998) to test the co-integration based upon the pseudo-likelihood ratio (PLR) trace test.

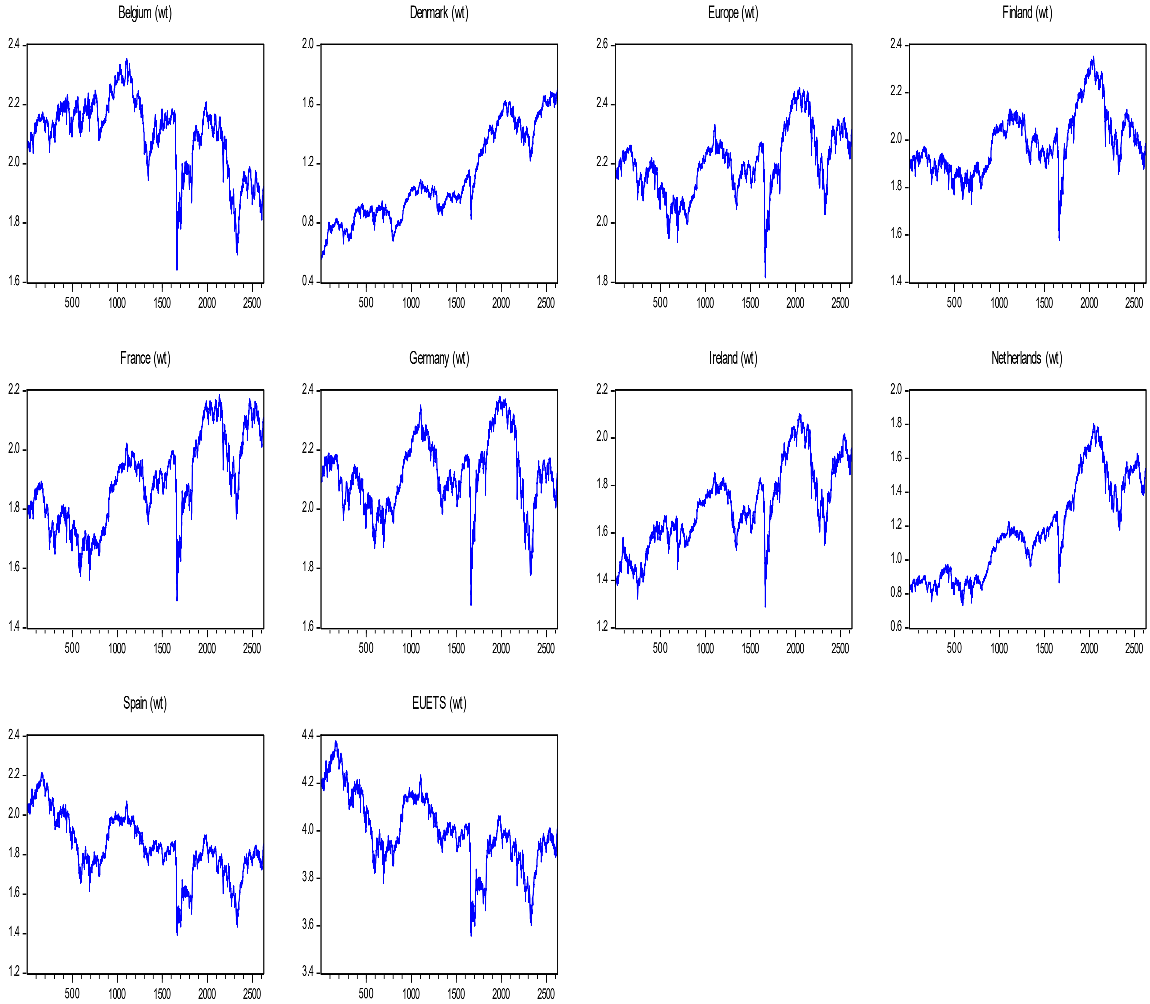

Figure 5. Weights (wt) assigned to the observations of European financial markets and carbon emission trading market (EUETS) indices.

Table 6. The table shows the co-integration test for the relationship between carbon emission trading market and European financial market indices.

	p	k-r
Belgium-EUETS	1	76.837 ***
	2	65.28 ***
Denmark-EU-ETS	1	71.937 ***
	2	59.83 ***
Finland-EUETS	1	49.192 ***
	2	39.827 ***
France-EUETS	1	88.428 ***
	2	86.812 ***
Germany	1	72.09 ***
	2	69.638 ***
Ireland-EUETS	1	99.10 ***
	2	61.837 ***
Italy-EUETS	1	55.021 ***
	2	47.39 ***
Netherlands-EUETS	1	59.172 ***
	2	50.10 ***
Spain	1	54.88 ***
	2	50.30 ***

Note: Co-integration test based upon outlier robust methodological framework used by Franses and Lucas (1998). The Asterisk signs of *** implies the rejection of null hypothesis at 1% level of significance.

Table 6 presents the pseudo-likelihood ratio (PLR) tests designed to evaluate the hypotheses H0: $r \leq 0$ against the alternative H1: r = 1. In this context, 'r' represents the number of co-integrating relations, 'p' signifies the order of the Vector Autoregressive (VAR) model utilized for test computation, and 'u' denotes the degrees-of-freedom parameter employed in the usual likelihood method. The symbols *, **, and *** signify significance levels at 10%, 5%, and 1%, respectively. Critical values are obtained from (Franses and Lucas 1998) under the conditions of drift. The superscripts 'a' and 'b' correspond to the order of the model associated with the minimum value of the Akaike and Schwarz Information Criteria, respectively.

5. Conclusions with Practical Implications and Future Research Directions

Due to the importance of emission prices and their potential correlation with financial assets, this study marks the first exploration into the prolonged co-integration and immediate impact of European carbon emission trading system (EU-ETS) returns and the CBOE oil price volatility index (OVZ) on the traditional financial structures of European economies, encompassing Belgium, Finland, France, Germany, Ireland, Italy, Netherlands, Spain, Denmark, and the entire Eurozone region. A thorough comprehension of the interactions between various financial market components, such as the stock and carbon markets, is necessary to develop portfolio allocation plans and carry out cross-market risk management. We utilize the co-integration test of Johansen and Juselius (1990) in conjunction with the ARDL technique of Pesaran et al. (2001) that incorporates an error-correcting mechanism (ECM). Furthermore, we calculate hedge ratios and optimal portfolio weights for long-term carbon risk mitigation using the DCC-GARCH-t copula technique.

Overall, the findings suggested that long-term co-integration is established between European carbon emission trading market (EU-ETS) returns, CBOE oil price volatility index, and financial market returns of Belgium, France, Germany, Spain and the whole European region. In existing scholarly works, Wen et al. (2020a) delineated the enduring co-integrating relationship between the returns of Chinese equities and those of China's carbon emission trading market. Conversely, Ceylan et al. (2020) substantiated the enduring co-integration between equity and stock returns within the purview of developing economies. Nevertheless, there exists a discernible gap in the literature, as no endeavors have been undertaken to investigate the co-integration among carbon trading, oil implied volatility, and the returns of the European financial market. In the long term, EU-ETS has an adverse effect of 10.22% and 10.13% on the financial market returns of Belgium and Spain, whereas EU-ETS has a significant positive effect of 9% and 3.98% on the financial market returns of France and the whole Eurozone. The deleterious effects observed in stock returns stemming from carbon emission trading markets may be attributed to the broader adverse responses of the overall economy to shocks within the carbon market. For example, the introduction of carbon emissions trading in China is anticipated to result in a statistically significant reduction in the country's gross domestic product (Li et al. 2018). However, it is noteworthy that this negative influence is expected to dissipate in the long term. Additionally, empirical evidence indicates a significant and negative correlation between carbon prices and the market value of thermal-listed enterprises in China (Zhang et al. 2018), with the magnitude of these effects varying across different markets. In contrast to the effect of EU-ETS on European financial market returns, the CBOE oil price volatility index has a consistent long-term adverse effect of 19.2%, 22.18%, 27.13%, and 19.41% on the financial market returns of France, Germany, Spain, and the Eurozone. Elevated oil prices induce augmented oil inventories, reduce oil consumption, and decelerate economic activity, leading to a depreciation in equity values (Gao et al. 2022). Moreover, empirical evidence indicates that, particularly during economic recessions, fluctuations in oil implied volatility exhibit a negative association with stock returns in African stock markets (Boateng et al. 2021). Our findings are consistent with prior research, underscoring the significant impact of oil market uncertainty on the realized volatility of stock markets in the Middle East and Africa. The authors underscore the heightened sensitivity of stock returns to variations in the implied oil volatility index (Dutta et al. 2017).

We propose several practical implications for long-term shareholders. For instance, in Belgium and Spain, long-term measures must be taken to mitigate the negative impact on stock returns without compromising environmental objectives. For instance, companies in Belgium and Spain could adopt long-term carbon reduction policies by transitioning from carbon-intensive to green energy resources. Utilizing green energy and internalizing carbon emission-free processes can act as a safeguard against escalating carbon prices, enhancing stock market performance in both countries. In the long term, the financial markets in France and the entire Eurozone demonstrated a positive response to the appreciation in carbon trading prices. Therefore, long-term shareholders from Belgium and Spain may identify investment opportunities in companies operating within France and the Eurozone that align with or benefit from the favorable impact of rising carbon trading prices on financial markets. The favorable ramifications of the carbon emission trading market align with extant research. A study conducted by Wen et al. (2020a) determined that the establishment of China's carbon emissions trading market exerts a positive influence on the surplus returns of enterprises engaged in carbon emission allowances trading. Furthermore, the study discerned a consistent upward trajectory in these returns post 2014. In contrast, another investigation by Bolton and Kacperczyk (2021) revealed that equities of companies exhibiting elevated total carbon dioxide emissions yield augmented returns. This finding implies that investors seek recompense for the inherent exposure to carbon emission risk associated with such firms.

In the short term, the European carbon emission trading market (CBOE oil price volatility index) has a more consistent positive (adverse) effect on all the financial market returns of Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Spain, and the Eurozone. We also intend to explore several practical ramifications for short-term traders in light of these findings. Hence, companies experiencing favorable stock price reactions to carbon emission trading market returns may be incentivized to adopt environmentally friendly policies, anticipating a positive influence on their stock performance. The favorable correlation between markets has the capacity to improve overall market efficiency. The swift dissemination of information and news across markets decreases the likelihood of price divergences and expedites the assimilation of relevant information by markets. Should the EU-ETS market exhibit a positive trend, it could set off a feedback loop, with equity market investors responding positively to this trend. Understanding these behavioral dynamics is vital for short-term speculators and regulators.

The strategy for selecting optimal portfolio weights demonstrates increased hedging effectiveness (HE), reaching 75% and 84%, in an effort to mitigate long-term volatility in EU-ETS through short-term positioning in Italy and Denmark, respectively. This suggests that, for a USD 1 bivariate portfolio encompassing both EU-ETS and stocks, a more substantial risk reduction of 75% and 84% can be achieved by allocating USD 0.25 and USD 0.16 to the Italian and Danish financial markets, respectively. Therefore, the optimal portfolio weight selection strategy prioritizes higher hedging effectiveness (HE) when adopting short-term positions in either the Italian or Danish equity markets to minimize the risk of long-term EU-ETS volatility in comparison to hedge ratios. Future studies should take into account the shock transmission mechanism between sustainable financial market returns and carbon emission trading returns in the context of European economies.

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Notes

[1] https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en. accessed on 1 October 2020.

References

Akin, Isik, Muhammad Zubair Khan, Affan Hameed, Kaouthar Chebbi, and Hakan Satiroglu. 2023. The ripple effects of CBDC-related news on Bitcoin returns: Insights from the DCC-GARCH model. *Research in International Business and Finance* 66: 102060. [CrossRef]

Al-Absy, Mujeeb Saif Mohsen. 2024. Board of Directors' Characteristics and Environmental Disclosure. In *Digital Technology and Changing Roles in Managerial and Financial Accounting: Theoretical Knowledge and Practical Application*. Leeds: Emerald Publishing Limited, pp. 267–77.

Alkathery, Mohammed, and Kausik Chaudhuri. 2021. Co-movement between oil price, CO_2 emission, renewable energy and energy equities: Evidence from GCC countries. *Journal of Environmental Management* 297: 113350. [CrossRef]

Antonakakis, Nikolaos, Juncal Cunado, George Filis, David Gabauer, and Fernando Perez de Gracia. 2018. Oil volatility, oil and gas firms and portfolio diversification. *Energy Economics* 70: 499–515. [CrossRef]

Asadi, Mehrad, Umaid A. Sheikh, Mehmet Balcilar, David Roubaud, and Hamid Reza Ghasemi. 2023. Are there inextricable connections among automobile stocks, crude oil, steel, and the US dollar? *Energy Economics* 128: 107176. [CrossRef]

Batten, Jonathan A., Grace E. Maddox, and Martin R. Young. 2021. Does weather, or energy prices, affect carbon prices? *Energy Economics* 96: 105016. [CrossRef]

Bibi, Ayesha, Xibao Zhang, and Muhammad Umar. 2021. The imperativeness of biomass energy consumption to the environmental sustainability of the United States revisited. *Environmental and Ecological Statistics* 28: 821–41. [CrossRef]

Boateng, Ebenezer, Anokye M. Adam, and Peterson Owusu Junior. 2021. Modelling the heterogeneous relationship between the crude oil implied volatility index and African stocks in the coronavirus pandemic. *Resources Policy* 74: 102389. [CrossRef]

Bohn Nielsen, Heino. 2004. Cointegration analysis in the presence of outliers. *The Econometrics Journal* 7: 249–71. [CrossRef]

Bolton, Patrick, and Marcin Kacperczyk. 2021. Do investors care about carbon risk? *Journal of Financial Economics* 142: 517–49. [CrossRef]

Bourghelle, David, Fredj Jawadi, and Philippe Rozin. 2021. Oil price volatility in the context of COVID-19. *International Economics* 167: 39–49. [CrossRef]

Bouri, Elie, David Gabauer, Rangan Gupta, and Aviral Kumar Tiwari. 2021. Volatility connectedness of major cryptocurrencies: The role of investor happiness. *Journal of Behavioral and Experimental Finance* 30: 100463. [CrossRef]

Bouri, Elie, Syed Jawad Hussain Shahzad, David Roubaud, Ladislav Kristoufek, and Brian Lucey. 2020. Bitcoin, gold, and commodities as safe havens for stocks: New insight through wavelet analysis. *The Quarterly Review of Economics and Finance* 77: 156–64. [CrossRef]

Breusch, Trevor S., and Adrian R. Pagan. 1979. A Simple Test for Heteroscedasticity and Random Coefficient Variation. *Econometrica* 47: 1287–94. [CrossRef]

Brouwers, Roel, Frederiek Schoubben, Cynthia Van Hulle, and Steve Van Uytbergen. 2016. The initial impact of EU ETS verification events on stock prices. *Energy Policy* 94: 138–49. [CrossRef]

Cepni, Oguzhan, Riza Demirer, and Lavinia Rognone. 2022. Hedging climate risks with green assets. *Economics Letters* 212: 110312. [CrossRef]

Ceylan, Resat, Mehmet Ivrendi, Muhammed Shahbaz, and Tolga Omay. 2020. Oil and stock prices: New evidence from a time varying homogenous panel smooth transition VECM for seven developing countries. *International Journal of Finance and Economics*, 1–16. [CrossRef]

Chen, Zhang-HangJian, Fei Ren, Ming-Yuan Yang, Feng-Zhi Lu, and Sai-Ping Li. 2023. Dynamic lead–lag relationship between Chinese carbon emission trading and stock markets under exogenous shocks. *International Review of Economics & Finance* 85: 295–305. [CrossRef]

Chun, Dohyun, Hoon Cho, and Jihun Kim. 2022. The relationship between carbon-intensive fuel and renewable energy stock prices under the emissions trading system. *Energy Economics* 114: 106257. [CrossRef]

Demiralay, Sercan, Hatice Gaye Gencer, and Selcuk Bayraci. 2022. Carbon credit futures as an emerging asset: Hedging, diversification and downside risks. *Energy Economics* 113: 106196. [CrossRef]

Dickey, David A., and Wayne A. Fuller. 1981. Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root. *Econometrica* 49: 1057–1072. [CrossRef]

Dong, Xiyong, Youlin Xiong, Siyue Nie, and Seong-Min Yoon. 2023. Can bonds hedge stock market risks? Green bonds vs conventional bonds. *Finance Research Letters* 52: 103367. [CrossRef]

Durbin, James, and Geoffrey S. Watson. 1951. Testing for Serial Correlation in Least Squares Regression. II. *Biometrika* 38: 159–77. [CrossRef]

Dutta, Anupam, Jussi Nikkinen, and Timo Rothovius. 2017. Impact of oil price uncertainty on Middle East and African stock markets. *Energy* 123: 189–97. [CrossRef]

Engle, Robert F., and Clive W. J. Granger. 1987. Co-integration and error correction: Representation, estimation, and testing. *Econometrica: Journal of the Econometric Society* 55: 251–76. [CrossRef]

Franses, Philip Hans, and André Lucas. 1998. Outlier Detection in Cointegration Analysis. *Journal of Business & Economic Statistics* 16: 459–68. [CrossRef]

Gao, Lin, Steffen Hitzemann, Ivan Shaliastovich, and Lai Xu. 2022. Oil volatility risk. *Journal of Financial Economics* 144: 456–91. [CrossRef]

Gourieroux, Christian, Alain Monfort, and Alain Trognon. 1984. Pseudo maximum likelihood methods: Theory. *Econometrica: Journal of the Econometric Society* 52: 681–700. [CrossRef]

Hadhri, Sinda. 2021. The nexus, downside risk and asset allocation between oil and Islamic stock markets: A cross-country analysis. *Energy Economics* 101: 105448. [CrossRef]

Hong, KiHoon, Hojin Jung, and Minjae Park. 2017. Predicting European carbon emission price movements. *Carbon Management* 8: 33–44. [CrossRef]

Hoque, Mohammad Enamul, Low Soo-Wah, and Mabruk Billah. 2023. Time-frequency connectedness and spillover among carbon, climate, and energy futures: Determinants and portfolio risk management implications. *Energy Economics* 127: 107034. [CrossRef]

Hu, Zinan, and Sumuya Borjigin. 2024. The amplifying role of geopolitical Risks, economic policy Uncertainty, and climate risks on Energy-Stock market volatility spillover across economic cycles. *The North American Journal of Economics and Finance* 71: 102114. [CrossRef]

Jiménez-Rodríguez, Rebeca. 2019. What happens to the relationship between EU allowances prices and stock market indices in Europe? *Energy Economics* 81: 13–24. [CrossRef]

Jin, Jiayu, Liyan Han, Lei Wu, and Hongchao Zeng. 2020. The hedging effect of green bonds on carbon market risk. *International Review of Financial Analysis* 71: 101509. [CrossRef]

Johansen, Søren, and K. Juselius. 1990. Maximum Likelihood Estimation and Inference on Cointegration: With Applications to the Demand Theory of Money. *Oxford Bulletin of Economics and Statistics* 1: 169–210. [CrossRef]

Johansen, Søren, Rocco Mosconi, and Bent Nielsen. 2000. Cointegration analysis in the presence of structural breaks in the deterministic trend. *The Econometrics Journal* 3: 216–49. Available online: http://www.jstor.org/stable/23114890 (accessed on 20 September 2020). [CrossRef]

Kroner, Kenneth F., and Jahangir Sultan. 1993. Time-Varying Distributions and Dynamic Hedging with Foreign Currency Futures. *Journal of Financial and Quantitative Analysis* 28: 535–51. Available online: https://econpapers.repec.org/RePEc:cup:jfinqa:v:28:y:1993:i:04:p:535-551_00 (accessed on 20 September 2020). [CrossRef]

Kroner, Kenneth F., and Victor K. Ng. 1998. Modeling Asymmetric Comovements of Asset Returns. *Review of Financial Studies* 11: 817–44. Available online: https://econpapers.repec.org/RePEc:oup:rfinst:v:11:y:1998:i:4:p:817-44 (accessed on 20 September 2020). [CrossRef]

Ku, Yuan-Hung Hsu, Ho-Chyuan Chen, and Kuang-Hua Chen. 2007. On the application of the dynamic conditional correlation model in estimating optimal time-varying hedge ratios. *Applied Economics Letters* 14: 503–9. [CrossRef]

Laskar, Najul, Nikhil Kulshrestha, Prakash Chandra Bahuguna, and Nitesh Kumar Adichwal. 2022. Carbon emission intensity and firm performance: An empirical investigation in Indian context. *Journal of Statistics and Management Systems* 25: 1073–81. [CrossRef]

Li, Wei, Yan-Wu Zhang, and Can Lu. 2018. The impact on electric power industry under the implementation of national carbon trading market in China: A dynamic CGE analysis. *Journal of Cleaner Production* 200: 511–23. [CrossRef]

Li, Xin, Zheng Li, Chi-Wei Su, Muhammad Umar, and Xuefeng Shao. 2022. Exploring the asymmetric impact of economic policy uncertainty on China's carbon emissions trading market price: Do different types of uncertainty matter? *Technological Forecasting and Social Change* 178: 121601. [CrossRef]

Liu, Jian, Yue Hu, Li-Zhao Yan, and Chun-Ping Chang. 2023. Volatility spillover and hedging strategies between the European carbon emissions and energy markets. *Energy Strategy Reviews* 46: 101058. [CrossRef]

Lucas, André. 1997. Cointegration testing using pseudolikelihood ratio tests. *Econometric Theory* 13: 149–69. [CrossRef]

MacKinnon, James, Alfred Haug, and Leo Michelis. 1999. Numerical Distribution Functions of Likelihood Ratio Tests for Cointegration. *Journal of Applied Econometrics* 14: 563–77. Available online: https://econpapers.repec.org/RePEc:jae:japmet:v:14:y:1999:i:5:p:563-77 (accessed on 20 September 2020). [CrossRef]

Mirza, Faisal Mehmood, and Afra Kanwal. 2017. Energy consumption, carbon emissions and economic growth in Pakistan: Dynamic causality analysis. *Renewable and Sustainable Energy Reviews* 72: 1233–40. [CrossRef]

Mo, Bin, Zhenghui Li, and Juan Meng. 2021. The dynamics of carbon on green energy equity investment: Quantile-on-quantile and quantile coherency approaches. *Environmental Science and Pollution Research*. [CrossRef]

Oestreich, A. Marcel, and Ilias Tsiakas. 2015. Carbon emissions and stock returns: Evidence from the EU Emissions Trading Scheme. *Journal of Banking & Finance* 58: 294–308. [CrossRef]

Ofori-Sasu, Daniel, Joshua Yindenaba Abor, George Nana Agyekum Donkor, and Isaac Otchere. 2023. Renewable energy consumption and carbon emissions in developing countries: The role of capital markets. *International Journal of Sustainable Energy* 42: 1407–29. [CrossRef]

Ouyang, Zisheng, Min Lu, and Yongzeng Lai. 2023. Forecasting stock index return and volatility based on GAVMD- Carbon-BiLSTM: How important is carbon emission trading? *Energy Economics* 128: 107134. [CrossRef]

Pablo-Romero, Maria del P., and Josué De Jesús. 2016. Economic growth and energy consumption: The energy-environmental Kuznets curve for Latin America and the Caribbean. *Renewable and Sustainable Energy Reviews* 60: 1343–50. [CrossRef]

Pal, Debdatta, and Subrata K. Mitra. 2015. Asymmetric impact of crude price on oil product pricing in the United States: An application of multiple threshold nonlinear autoregressive distributed lag model. *Economic Modelling* 51: 436–43. [CrossRef]

Pesaran, M. Hashem, Yongcheol Shin, and Richard J. Smith. 2001. Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics* 16: 289–326. [CrossRef]

Phillips, Peter C. B., and Pierre Perron. 1988. Testing for a unit root in time series regression. *Biometrika* 75: 335–46. [CrossRef]

Ramsey, James Bernard. 1969. Tests for Specification Errors in Classical Linear Least Squares Regression Analysis. *Journal of the Royal Statistical Society, Series B* 31: 350–71. [CrossRef]

Razzaq, Asif, Arshian Sharif, Hui An, and Chaker Aloui. 2022. Testing the directional predictability between carbon trading and sectoral stocks in China: New insights using cross-quantilogram and rolling window causality approaches. *Technological Forecasting and Social Change* 182: 121846. [CrossRef]

Sharma, Rajesh, Muhammad Shahbaz, Avik Sinha, and Xuan Vinh Vo. 2021. Examining the temporal impact of stock market development on carbon intensity: Evidence from South Asian countries. *Journal of Environmental Management* 297: 113248. [CrossRef]

Sheikh, Umaid A., Mehrad Asadi, David Roubaud, and Shawkat Hammoudeh. 2024. Global uncertainties and Australian financial markets: Quantile time-frequency connectedness. *International Review of Financial Analysis* 92: 103098. [CrossRef]

Sousa, Rita, Luís Aguiar-Conraria, and Maria Joana Soares. 2014. Carbon Financial Markets: A Time–Frequency Analysis of CO2 Prices. *Physica A: Statistical Mechanics and Its Applications* 414: 118–27. [CrossRef]

Suleman, Muhammad Tahir, Mobeen Ur Rehman, Umaid A. Sheikh, and Sang Hoon Kang. 2023a. Dynamic time-frequency connectedness between European emissions trading system and sustainability markets. *Energy Economics* 123: 106726. [CrossRef]

Suleman, Muhammad Tahir, Mosab I. Tabash, and Umaid A. Sheikh. 2022. Do stock market fluctuations lead to currency deflation in the South Asian region? Evidence beyond symmetry. *International Journal of Finance & Economics*. [CrossRef]

Suleman, Muhammad Tahir, Umaid A. Sheikh, Emilios C. Galariotis, and David Roubaud. 2023b. The impact of bitcoin fear and greed on good and bad network connectedness: The case of the US sectoral high frequency returns. *Annals of Operations Research*. [CrossRef]

Sun, Xiaotian, Wei Fang, Xiangyun Gao, Haizhong An, Siyao Liu, and Tao Wu. 2022. Complex causalities between the carbon market and the stock markets for energy intensive industries in China. *International Review of Economics & Finance* 78: 404–17. [CrossRef]

Tabash, Mosab I., Neenu Chalissery, T. Mohamed Nishad, and Mujeeb Saif Mohsen Al-Absy. 2024. Market Shocks and Stock Volatility: Evidence from Emerging and Developed Markets. *International Journal of Financial Studies* 12: 2. [CrossRef]

Tan, Xueping, Kavita Sirichand, Andrew Vivian, and Xinyu Wang. 2020. How connected is the carbon market to energy and financial markets? A systematic analysis of spillovers and dynamics. *Energy Economics* 90: 104870. [CrossRef]

Teixidó, Jordi, Stefano F. Verde, and Francesco Nicolli. 2019. The impact of the EU Emissions Trading System on low-carbon technological change: The empirical evidence. *Ecological Economics* 164: 106347.

Wang, Lu, Gong-li Luo, Arshian Sharif, and Gheorghita Dinca. 2021. Asymmetric dynamics and quantile dependency of the resource curse in the USA. *Resources Policy* 72: 102104. [CrossRef]

Weitzman, Martin L. 2014. Fat Tails and the Social Cost of Carbon 2014. Fat tails and the social cost of carbon. *American Economic Review* 104: 544–46. [CrossRef]

Wen, Fenghua, Lili Zhao, Shaoyi He, and Guozheng Yang. 2020a. China's carbon emissions trading and stock returns. *Energy Economics* 86: 104627. [CrossRef]

Wen, Fenghua, Nan Wu, and Xu Gong. 2020b. Asymmetric relationship between carbon emission trading market and stock market: Evidences from China. *Energy Economics* 91: 104850. [CrossRef]

Yadav, Miklesh Prasad, Taimur Sharif, Shruti Ashok, Deepika Dhingra, and Mohammad Zoynul Abedin. 2023. Investigating volatility spillover of energy commodities in the context of the Chinese and European stock markets. *Research in International Business and Finance* 65: 101948. [CrossRef]

Yang, LI, Jingqiu Luo, and Yongmu Jiang. 2021. Policy uncertainty spillovers and financial risk contagion in the Asia-Pacific network. *Pacific-Basin Finance Journal* 67: 101554. [CrossRef]

Yin, Yingkai, Zhihui Jiang, Yazhou Liu, and Zheng Yu. 2019. Factors Affecting Carbon Emission Trading Price: Evidence from China. *Emerging Markets Finance and Trade* 55: 3433–51. [CrossRef]

Yu, Zhi, Yali Cao, and Mo Liu. 2022. Does carbon emission trading policy affect bank loans of firms? Evidence from China. *Applied Economics Letters* 29: 1709–14. [CrossRef]

Zhang, Fang, Hong Fang, and Xu Wang. 2018. Impact of Carbon Prices on Corporate Value: The Case of China's Thermal Listed Enterprises. *Sustainability* 10: 3328. [CrossRef]

Zhang, Junchao, and Wei Han. 2022. Carbon emission trading and equity markets in China: How liquidity is impacting carbon returns? *Economic Research-Ekonomska Istraživanja* 35: 6466–78. [CrossRef]

Zhang, Zheng, Muhammad Yousaf Raza, Wenxue Wang, and Lu Sui. 2023. Volatility Predictability in Crude Oil Futures: Evidence Based on OVX, GARCH and Stochastic Volatility Models. *Energy Strategy Reviews* 50: 101209. [CrossRef]

Zhao, Zuoxiang, Chi Keung Marco Lau, Alaa Soliman, and Sahbi Farhani. 2023. Energy commodity and stock market interconnectedness: Evidence from carbon emission trading system. *Technological Forecasting and Social Change* 194: 122669. [CrossRef]

Zheng, Yan, Min Zhou, and Fenghua Wen. 2021. Asymmetric effects of oil shocks on carbon allowance price: Evidence from China. *Energy Economics* 97: 105183. [CrossRef]

Zivot, Eric, and Donald W. K. Andrews. 1992. Further Evidence on the Great Crash, the Oil-Price Shock, and the Unit-Root Hypothesis. *Journal of Business & Economic Statistics* 10: 251–70. [CrossRef]