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Evidence for price discovery between carbon emission and equity markets: Evidence from time and frequency domains

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A R T I C L E I N F O

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A B S T R A C T

This study examines the dynamic relationship between the carbon emissions market and stock markets in emerging European countries (the Czech Republic, Greece, Hungary, and Poland). We employ the frequency-domain causality test developed by Breitung and Candelon (2006) to identify short- and long-term causality relationships among the variables. Additionally, a rolling-window frequency-domain causality test is employed to capture the time-varying nature of the relationship between the carbon and stock markets. The empirical results reveal a primary causal relationship running from the stock market to the carbon market, with the intensity of this causality increasing during periods of market turbulence, such as the global financial crisis, COVID-19, and the Russia–Ukraine conflict. This suggests that equity markets may serve as early signals of carbon prices, particularly during periods of market stress. Such insights could be particularly valuable for central banks when calibrating their respective monetary policies.

1. Introduction

Since the Industrial Revolution, technological advances have dramatically accelerated the pace of progress. Investments in technology, substantial funding for research and development, and breakthroughs in academic research have transformed our environment over recent decades. These advances undoubtedly serve humanity by addressing societal needs. However, as with many great developments, they also carry a cost. These advancements have been associated with rising carbon dioxide concentrations, increasing global temperatures, and, ultimately, global warming. These side effects, including rising sea levels, more severe natural disasters, loss of biodiversity, and decreased agricultural productivity, pose significant threats to life on Earth.

Addressing the damage caused by global warming and mitigating its future impacts requires global coordination rather than individual country- or region-based initiatives. In this context, significant agreements have been adopted under the UN Framework Convention on Climate Change, from the Kyoto Protocol in 1997 to the Paris Agreement in 2015. According to Falkner (2016), the Kyoto Protocol primarily focused on enforcing greenhouse gas emission reductions among 37 industrialized countries, whereas the Paris Agreement expanded its scope to include all nations in the pursuit of global climate goals. One notable mechanism introduced during this period to combat global warming was the carbon trading system, a tool designed to mitigate the climate crisis. This system allows companies to purchase carbon credits from others with surplus emission allowances. These credits are tradable certificates that represent greenhouse gas reductions or removals. The carbon market operates through two primary mechanisms: allowance trading (the cap-and-trade approach) and offset credits trading (the baseline-and-credit approach) (Lefevere, 2005). The uneven distribution of greenhouse gas emissions across industries facilitates the functioning of this market. For example, sectors such as aviation and maritime transport, which are inherently reliant on fossil fuels, lead to higher emissions, whereas other sectors exhibit greener energy consumption practices. This imbalance creates opportunities for trading within the carbon market. However, challenges such as greenwashing—where companies falsely claim to meet sustainability goals—pose risks to the credibility of the carbon market by undermining its effectiveness in reducing emissions.

Despite these issues, carbon markets hold significant potential to advance global warming mitigation efforts and achieve emission-reduction targets. The concept of carbon trading originated with the Kyoto Protocol, under which excess emission units could be traded among countries. This mechanism has evolved into what is today widely

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known as the carbon market. According to Perdan and Azapagic (2011), among these markets, the European Union (EU) Emissions Trading System (ETS) stands out as a pillar of EU climate policy, a leading model for carbon pricing, and the primary mechanism for fulfilling the EU's commitments under the Kyoto Protocol. The EU ETS operates on a cap-and-trade mechanism, where the EU establishes a limit on greenhouse gas emissions and allocates European Emission Allowances (EUAs) to entities. These allowances, typically acquired through auctions, confer the right to emit one metric ton of CO_2 equivalent and may be traded on the carbon market. Firms that maintain their emissions below their allocated caps can sell their surplus allowances, with prices determined by the prevailing supply and demand.

In the empirical section of this study, we examine the relationship between the EU ETS carbon price index and the equity-market indices of four emerging European economies. The literature highlights a positive relationship between firm-level sustainability initiatives and improved financial metrics. Fatemi et al. (2018), Aydoğmuş, Gülay, and Ergun (2022), and Wong et al. (2021) confirmed that initiatives aimed at achieving higher sustainability scores are significantly associated with firm value, profitability, and borrowing costs. Furthermore, as demonstrated by Maaloul et al. (2023), sustainability efforts significantly affect public perception and enhance reputation. However, unlike these studies, we use carbon prices as a proxy for sustainability instead of relying on environmental, social, and governance metrics or corporate social responsibility scores. This approach is justified because carbon prices reflect market demand for emission allowances, which is influenced by factors such as fossil-fuel consumption, policy interventions, and market expectations. Therefore, carbon price movements provide a direct market-based measure of firms' emission-related costs and regulatory exposure, offering a natural channel through which sustainability considerations are transmitted to equity valuations—a mechanism formally developed in the following hypothesis framework.

Carbon allowance prices convey economically meaningful information about firms' regulatory exposure, production costs, and expected profitability. Within a cap-and-trade framework, rising carbon prices indicate greater demand for emission allowances driven by higher fossil-fuel reliance, tighter emission caps, or anticipated regulatory tightening. In contrast, declining prices signal lower emission intensity or a transition toward cleaner energy sources. At the firm and sectoral levels, higher carbon prices increase marginal production costs—particularly in carbon-intensive industries—through higher allowance expenditures and energy input costs, thereby compressing operating margins and increasing earnings volatility. From a regulatory standpoint, carbon pricing under the EU ETS operates as a market-based instrument that internalizes emission costs and directly affects firms' cost structures. According to Weyl and Fabinger (2013), under the cost pass-through theory, increases in regulatory and input costs are transmitted to prices and profit margins, reducing expected cash flows and increasing risk. Under standard asset-pricing principles, these effects are capitalized into lower equity valuations.

Additionally, Oestreich and Tsiakas (2015) identified two complementary channels through which carbon prices affect stock returns within the EU ETS: a cash-flow and a carbon-risk effect. The cash-flow effect arises because changes in allowance prices alter firms' marginal production costs and profitability—particularly for emission-intensive firms—while the carbon-risk effect reflects uncertainty about future allowance prices and regulatory adjustments, increasing cash-flow volatility and required returns. Conversely, declining carbon prices reduce compliance costs and ease regulatory pressure, thereby supporting profitability and firm valuation. These channels are likely to intensify during periods of market stress, when energy price shocks, policy uncertainty, and liquidity constraints amplify the sensitivity of equity returns to regulatory cost signals embedded in carbon prices. Furthermore, given the forward-looking nature of equity markets, stock prices may adjust more rapidly than carbon markets during crisis episodes, as investors reassess firms' expected exposure to future emission limits and regulatory tightening.

Consistent with this distinction, Aswani et al. (2024) showed that firm-level carbon emissions are not robustly priced in equity returns once measurement issues are addressed. In contrast, market-based carbon allowance prices remain economically relevant for valuation because they directly affect firms' regulatory costs and risk exposure. The second hypothesis examines carbon taxation as an additional regulatory mechanism in a conceptual and comparative context. Drawing on regulatory intensity theory, more stringent environmental regulation may increase firms' exposure to compliance costs and strategic adjustment pressures. As argued by Porter and Linde (1995), greater regulatory intensity can alter firms' cost structures, innovation incentives, and competitive behavior, potentially strengthening the transmission of environmental policy signals to corporate performance. Following Mengden (2024), we distinguish countries by the presence or absence of carbon taxation and conduct a descriptive, sample-based comparison between Hungary and Poland (with carbon taxation) and Greece and the Czech Republic (without carbon taxation). Importantly, carbon taxation is not modeled explicitly in the econometric framework. Accordingly, the comparison is exploratory in nature and is designed to determine whether equity–carbon market interactions exhibit observable differences across regulatory environments, without implying causal interpretation.

Unlike much of the literature (Dutta et al., 2018; Tian et al., 2016; Wen et al., 2020), our investigation leverages frequency-domain analyses to capture interactions over both short- and long-term cycles, providing valuable insights for investors across different time horizons. For instance, short-term investors are more influenced by daily price fluctuations, whereas long-term investors focus on market fundamentals. Evidence of long-term interactions can indicate a stable, established relationship between variables, such as carbon and equity markets. This insight could encourage policymakers to design incentives that promote companies' use of greener resources. Conversely, short-term evidence may reflect temporary or less pronounced interactions, guiding policymakers toward formulating targeted regulations that encourage sustainable business practices. From this perspective, our findings are valuable to both policymakers and the public. Policymakers can design effective strategies to foster sustainability, while the public benefits from a cleaner environment and more sustainable economic practices. To align with these objectives, we employ the frequency-domain causality approach developed by Breitung and Candelon (2006), complemented by wavelet coherence analysis as a robustness check to obtain more reliable insights. Moreover, in contrast to earlier studies (Gokmenoglu et al., 2019; Joseph et al., 2014; Ciner, 2011), we extend the BC framework to incorporate time-varying dynamics. This dynamic causality analysis enables us to evaluate how major geopolitical events—such as the pandemic, the Russia–Ukraine war, the Israeli–Palestinian conflict, and the Syrian war—may have influenced investor behavior and policy responses in unpredictable ways. By comparing these results with those obtained from dynamic wavelet coherence analysis, we strengthen the robustness and depth of our findings.

Importantly, although studies have documented crisis-driven, time-varying, and asymmetric spillovers in developed markets and composite energy indices, our findings indicate a distinct pattern in emerging European equity markets. Specifically, the direction of information flow runs predominantly from stock markets to the carbon market, with carbon-to-equity effects being more episodic and frequency specific rather than persistent. This pattern suggests that well-established stylized facts in the literature manifest differently in emerging-market settings, particularly with respect to the direction and temporal persistence of spillovers.

Overall, this study makes two contributions to the literature. First, it is among the first attempts to explore the relationship between the carbon emissions market and stock markets in emerging Europe, in contrast with existing research that generally focuses on developed countries' stock markets or relies on broad market indices. Second, it introduces an innovative econometric approach by applying time-varying frequency-domain causality analysis to the research on carbon markets. Collectively, these contributions extend the literature by showing how commonly reported findings—such as stronger linkages during crises and time-varying causality—exhibit different characteristics in emerging equity markets, thereby providing new empirical insights beyond developed-market settings.

In the following sections of the study, we present findings from leading studies that support the framework outlined above. Next, we introduce the theoretical background of the econometric framework. The empirical analysis section presents our statistical findings and their implications for market dynamics. We next present the robustness checks results. Finally, we conclude by discussing our findings in the context of econometrics and their implications for various stakeholders, including policymakers, the public, and investors.

2. Literature review

The interaction between carbon emission trading markets and other financial and real sectors is attracting increasing scholarly attention, reflecting the expanding role of market-based climate policies and the growing incorporation of environmental risks into asset-pricing frameworks. Consequently, the literature spans a range of disciplines, from climate science and energy economics to macroeconomic and policy analysis. From a climate science perspective, carbon emissions generate long-lasting and potentially irreversible effects on the climate system, underscoring the economic urgency of timely mitigation efforts (Narayan et al., 2016; Solomon et al., 2009). Building on this foundation, Hansen et al. (2013) argued that rapid and substantial reductions in fossil-fuel carbon emissions—supported by a rising carbon price—are essential to restore the Earth's energy balance, avoid irreversible climate damage, and limit long-term intergenerational costs. Complementing these climate-driven arguments, the policy-oriented literature highlights that alternative climate policy instruments can lead to markedly different economic, environmental, and emissions outcomes. In this context, Li and Lin (2013) show that effective reductions in carbon intensity require carefully designed policy mixes that explicitly balance trade-offs between absolute and intensity-based emission controls. Similarly, Can and Can (2025) demonstrated that consumption-based carbon-reduction programs in OECD countries effectively reduce emissions, with output dynamics and foreign trade playing central roles. They further identify environmental taxes—particularly when coupled with green finance—as critical instruments for advancing renewable energy use and environmental sustainability. More recent empirical evidence finds that climate vulnerability and economic structures systematically shape carbon emissions and sustainability outcomes, reinforcing the macroeconomic underpinnings of carbon markets and their interaction with broader economic systems (Rehman et al., 2022; Ren et al., 2024). Extending this perspective to energy markets, Zhao et al. (2023) examined the relationship between EU carbon prices and Northern European electricity markets using VAR and GARCH models, concluding that the linkage is predominantly indirect, operating through fluctuations in energy prices.

In addition to the concepts discussed above, interest in the interaction between carbon emission trading and equity markets is also growing. One strand of the literature focuses on the relationship between carbon prices and stock market returns or volatility, motivated by the idea that carbon costs may directly affect firms' profitability, risk exposure, and valuation through their impact on production costs, regulatory compliance, and investment decisions. Using a VAR-based Granger causality framework, Kumar et al. (2012) analyzed the joint dynamics of carbon prices, clean-energy stock indices, technology stocks, and oil prices. Their findings suggest that carbon prices do not significantly affect stock returns owing to a relatively weak transmission mechanism in the early phase of carbon market development. Subsequent studies using firm-level or sectoral data reveal more heterogeneous effects. Employing a multivariate GARCH framework for firms listed in the Stoxx Europe Total Market Index, Venmans (2015) showed that the effect of carbon prices on stock prices varies significantly across firms, although the average effect is positive. Similarly, Oestreich and Tsiakas (2015) found that German firms that received free emission allowances outperformed those without such allowances, underscoring the importance of regulatory design in shaping market outcomes. Sector-level evidence further indicates that the carbon–equity relationship varies across industries and by energy intensity. Tian et al. (2016) investigated electricity companies operating under the EU ETS using a combination of OLS, panel regressions, and time-series methods, finding that both the magnitude and volatility of stock returns respond to carbon prices in a time-varying manner. Their findings suggest that major market disruptions and regulatory changes can modify both the strength and direction of the relationship. Extending this line of research, Dutta et al. (2018) examined volatility spillovers between EU carbon prices and clean-energy stock indices within a VAR–GARCH framework, finding a positive, statistically significant effect of carbon prices on European clean-energy stocks. In contrast, no comparable effect was detected in the U.S. market, suggesting regional heterogeneity in carbon–financial market linkages. In the EU context, Qiu et al. (2023) employed a time-varying parameter VAR model to examine the joint dynamics among carbon, stock, and renewable energy markets. Their findings show that the direction and intensity of spillovers evolve, with carbon markets exerting a negative influence on stock markets in the short run, yet the effect becomes negligible in the medium term. Notably, during the COVID-19 pandemic, the relationship turned positive, underscoring the importance of crisis periods in shaping market interactions. Collectively, these studies show that the influence of carbon markets on stock returns and volatility is neither uniform nor stable over time. That linear, full-sample approaches may mask important dynamics.

Equity markets and a broader set of financial assets have been examined to identify the financial drivers of carbon emissions. Within this growing literature, green finance has received particular attention. Saha and Maji (2025) provided cross-country evidence from 44 developed and developing economies showing that green bond issuance is associated with a statistically significant decline in CO_2 emissions, with stronger mitigation effects observed in developing countries. Rannou et al. (2021) analyzed the interaction between green bonds and carbon markets in the European context by examining the trading behavior of power firms, documenting that green bonds initially complemented carbon futures for short-term hedging and speculative activity, while increasingly substituting for carbon futures for long-term hedging after 2018. Consistent with this market-based perspective, Leitão et al. (2021) employed a Markov-switching framework and showed that green bonds positively influence EU ETS carbon prices across both high- and low-volatility regimes.

In contrast, conventional bonds and energy commodities are associated with declines in carbon prices during periods of heightened volatility. In addition to pricing effects in carbon markets, recent evidence shows that carbon exposure is reflected in fixed-income investment behavior. Cao et al. (2025) demonstrated that greater corporate carbon exposure leads to investor outflows from corporate bond mutual funds, triggering sales of high-carbon bonds and deteriorating bond liquidity, particularly for securities heavily held by mutual funds.

At the broader market level, the interconnectedness between financial markets and carbon-related assets has also been documented. Using a modified minimum spanning tree network approach, Zheng et al. (2013) identified stable linkages among similar financial assets. They uncovered a pronounced lead–lag structure in which stock market volatility precedes volatility in EU carbon allowances and crude oil futures. Several studies have examined carbon emissions at the sectoral and commodity levels by extending the analysis from financial markets to real economic activities. Csillik and Asner (2020) provided spatially-grounded evidence that gold mining in the Peruvian Amazon generates significant aboveground carbon emissions that are highly concentrated in particular mining areas, including protected zones and their ecological buffer regions. From a global production perspective, Ulrich et al. (2022) found that the introduction of carbon pricing materially increases gold production costs on a country-specific basis, reshapes relative cost competitiveness across producers, and creates incentives for emissions reductions through energy substitution and efficiency improvements. Country-level evidence further supports these findings. Ali et al. (2022) showed that positive shocks to gold prices mitigate environmental pollution in South Africa, while renewable energy consumption improves environmental quality in the short and long run. Similarly, Lu et al. (2024) documented that oil price shocks have statistically significant short-term effects on oil firms' financial performance and are positively associated with carbon emissions over longer horizons. Collectively, this strand of the literature suggests that financial instruments, market interconnectedness, commodity price dynamics, and resource-intensive production activities are jointly linked to carbon emission outcomes across markets, sectors, and regions.

Complementing the EU-focused literature, a large body of research examines carbon markets in other countries—most notably China—-which differ markedly from the EU ETS in terms of market maturity, regulatory design, and operational efficiency. Early research by Zhao et al. (2017) assessed the informational efficiency of China's carbon market using unit root and run tests, concluding that the market is only weak-form efficient. This lack of efficiency implies incomplete price discovery and suggests that interactions between carbon prices and financial markets may be unstable or nonlinear. Subsequent studies have documented complex and heterogeneous linkages between China's carbon market and equity markets. For example, employing spillover analysis and multifractal cross-correlation techniques, Xu et al. (2022) found significant nonlinear dependence and higher volatility in carbon prices relative to stock markets. Using a pattern causality framework, Sun et al. (2022) reported generally weak causal relationships between carbon allowance prices and sectoral stock indices, whereas Dong et al. (2024) showed that China's carbon market often acts as a net volatility receiver with sector-dependent spillover structures. Recent research has extended this line of inquiry to fixed-income markets, providing growing evidence that carbon-related risks are incorporated into bond pricing. Si and Zhang (2025) showed that carbon emission disclosure is associated with lower corporate bond credit spreads, with a particularly pronounced effect for firms operating under stricter environmental regulations, suggesting that bond investors value carbon-related information. Focusing on risk exposure rather than disclosure, Wu and Tian (2022) found that Chinese bond issuers with higher carbon-risk face significantly wider credit spreads, especially among financially constrained firms and those not undertaking a green transition, indicating that investors demand a carbon-risk premium. Complementing these pricing-based findings, Guo et al. (2023) adopted a dynamic connectedness framework and found that, within the Chinese carbon–energy–finance system, the carbon–stock market serves as a persistent net transmitter of shocks. In contrast, the carbon bond market—particularly the carbon-neutral bond segment—primarily serves as a net receiver and risk absorber. Risk-oriented and policy-focused studies further emphasize the importance of stress periods and regulatory context. Zhang et al. (2022) showed that spillovers from stock to carbon markets intensified during the 2015 Chinese stock market crisis, suggesting an information-leadership role for equity markets. At the policy level, Li and Jia (2017) found that policy frameworks combining emission trading schemes and carbon taxation achieve greater emissions reductions and stronger reductions in energy consumption than single-instrument approaches. Thus, policy effectiveness depends on the configuration and intensity of carbon mitigation instruments. Collectively, this evidence supports the idea that China's carbon market is episodically integrated with financial markets, with stronger linkages emerging during periods of economic stress and regulatory transition.

In addition to research on China, another strand of literature examines the economic, structural, and policy determinants of carbon emissions across emerging and developing economies. Focusing on Turkey, Ozturk and Acaravci (2010) investigated the long-run relationship among carbon emissions, energy consumption, employment, and economic growth using ARDL bounds testing and Granger causality analysis. They documented stable long-run linkages while showing that short-run causality runs from employment to economic growth rather than from emissions or energy use. Ozturk and Acaravci (2013) extended this analysis by incorporating trade openness and financial development, finding that increased trade openness increases carbon emissions in Turkey. In contrast, financial development does not exert a significant long-run effect, which is consistent with the environmental Kuznets curve hypothesis. At a continental scale, Williams et al. (2007) demonstrated Africa's critical role in the global carbon cycle, showing that land-use change and climate variability generate substantial interannual fluctuations in carbon emissions and heighten the continent's vulnerability to future climate change. Using a macropanel framework, Olubusoye and Musa (2020) provided limited empirical support for the environmental Kuznets curve in Africa, showing that economic growth is associated with rising emissions in most countries. From a policy-oriented perspective, Couth and Trois (2010) emphasized the mitigation potential of improved municipal solid waste management, demonstrating that waste separation and composting can significantly reduce greenhouse gas emissions in African cities. More recently, Ayimadu et al. (2024) employed linear, nonlinear, and ensemble machine learning techniques across 48 African countries, showing that economic expansion and energy consumption are the primary drivers of CO_2 emissions, while natural resource rents influence environmental sustainability dynamics.

3. Econometric framework

In determining the econometric framework, our primary objective is to extract economically meaningful information consistent with the fundamental role of carbon markets. Carbon emissions and their interactions with financial assets extend beyond short-term price dynamics and transitory market fluctuations. Rather, carbon pricing—particularly within the EU ETS—was established under international climate initiatives, beginning with the Kyoto Protocol, to support long-term sustainability and decarbonization through market-based regulatory mechanisms. Consequently, carbon prices are intrinsically linked to macroeconomic policy decisions, regulatory commitments, and long-horizon transition dynamics, rather than merely reflecting daily price movements or noise-driven behavior.

Conventional time-domain analyses aggregate effects across all horizons, thereby obscuring whether carbon–temporary market reactions or persistent, policy-relevant mechanisms drive equity linkages. This distinction is particularly important in the context of carbon markets, where economic relevance differs sharply across time horizons. As argued by Baruník and Křehlík (2018), short-term interactions often capture trading behavior, liquidity conditions, and temporary shocks. In contrast, medium- and long-term interactions reflect structural adjustments related to energy consumption patterns, industrial transformation, and regulatory intensity. Accordingly, as highlighted by Gunay et al. (2025), short- and long-horizon dynamics may convey distinct information for investors and policymakers.

From an economic perspective, the long-horizon components of carbon–equity interactions are especially informative, as they align with policy design horizons, regulatory evaluation cycles, and strategic investment decisions associated with sustainability transitions. At the same time, higher-frequency dynamics primarily reflect market microstructure and speculative behavior. Distinguishing between these channels is essential for interpreting the economic content of carbon–equity spillovers. We address this issue by employing frequency-domain causality analysis and wavelet-based methods to decompose interactions across multiple frequency bands and identify how the strength and direction of carbon–equity linkages vary across investment horizons. Using this framework, we can assess whether carbon prices transmit information to equity markets predominantly through short-term financial channels or longer-term sustainability and regulatory channels. This insight cannot be obtained from time-domain analysis alone.

3.1. Frequency-domain causality test

This study examines the relationship between the carbon and stock markets using the frequency-domain Granger causality (FDGC) test developed by Breitung and Candelon (2006). This test, which allows identification of both short- and long-term causal relationships between variables, is widely employed in the literature. This is particularly important for carbon markets, as previous evidence from Asl et al. (2022) and Wen et al. (2020) shows that carbon–stock price linkages differ across short- and long-term frequencies.

A rolling-window methodology is utilized to estimate the VAR model, and the FDGC test is performed on individual subsamples, facilitating an analysis of the shifting causal associations between the carbon and stock markets. Given the significant structural changes introduced in the four distinct phases of the EU ETS since its inception, using a time-varying test method is particularly important for the carbon market. In this regard, Lin and Zhang (2022) identified 15 structural breakpoints in the EU carbon emission allowance price, showing that accounting for these structural breaks significantly improves forecasting accuracy, underscoring the importance of capturing such dynamics in predictive models. Creti et al. (2012) emphasized that the equilibrium relationship between carbon prices and their determinants varied between the first and second phases, while Feng et al. (2012) found differences in the downward and upward risks in the carbon market across these phases.

The FDGC test builds on the foundational studies of Geweke (1982), Yao and Hosoya (1991), and Hosoya (2001). If we define $z_t = [x_t, y_t]'$ as a two-dimensional vector of time-series observed at $t = 1, \ldots,$ T, the finite-order VAR model for z_t can be written as follows:

$$\Theta(L)z_t = \varepsilon_t, \tag{1}$$

where $\Theta(L) = 1 - \Theta_1 L - \ldots - \Theta_p L^p$ is a 2 × 2 lag polynomial with $L^m z_t = z_{t-m}$.

BC (2006) showed that the moving average representation of the VAR model can be written as follows:

$$z_t = \Phi(L)\varepsilon_t = \begin{bmatrix} \Phi_{11}(L) & \Phi_{12}(L) \\ \Phi_{21}(L) & \Phi_{22}(L) \end{bmatrix} \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{bmatrix}, \tag{2}$$

$$\Psi(L)\eta_t = \begin{bmatrix} \Psi_{11}(L) & \Psi_{12}(L) \\ \Psi_{21}(L) & \Psi_{22}(L) \end{bmatrix} \begin{bmatrix} \eta_{1t} \\ \eta_{2t} \end{bmatrix}, \tag{3}$$

where $\Phi(L) = \Theta(L)^{-1}$ and $\Psi(L) = \Phi(L)G^{-1}$. The spectral density of x_t can be defined as

$$f_x(\omega) = \frac{1}{2\pi}\left\{ \left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2 + \left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2 \right\}. \tag{4}$$

Geweke (1982) and Hosoya (2001) defined the causal link from y to x at a given frequency (ω) as follows:

$$M_{y\to x}(\omega) = log\left[\frac{2\pi f_x(\omega)}{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2}\right] = log\left[1 + \frac{\left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2}{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2}\right]. \tag{5}$$

The null hypothesis of no Granger causality from y to x at frequency ω cannot be rejected if $\left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2 = 0$. However, BC (2006) highlighted the method's intricate nature and suggested a more straightforward alternative for testing the hypothesis. This approach involves using $\Psi(L) = \Theta(L)^{-1}G^{-1}$ and $\Psi_{12}(L) = -\frac{g^{22}\Theta_{12}(L)}{|\Theta(L)|}$, where g^{22} is the lower diagonal entry of G^{-1} and $|\Theta(L)|$ denotes the determinant of $\Theta(L)$. Hence, the absence of Granger causality from y to x at frequency ω is confirmed when $\left|\Theta_{12}\left(e^{-i\omega}\right)\right| = 0$, as shown below:

$$\left|\Theta_{12}\left(e^{-i\omega}\right)\right| = \left|\sum_{k=1}^{p}\theta_{12,k}\cos(k\omega) - \sum_{k=1}^{p}\theta_{12,k}\sin(k\omega)i\right| = 0, \tag{6}$$

where $\theta_{12,k}$ is the (1,2)-element of Θ_k. Thus, a necessary and sufficient set of conditions for $\left|\Theta_{12}\left(e^{-i\omega}\right)\right| = 0$ can be written as follows:

$$\sum_{k=1}^{p}\theta_{12,k}\cos(k\omega) = 0 \text{ and } \sum_{k=1}^{p}\theta_{12,k}\sin(k\omega) = 0 \tag{7}$$

BC (2006) demonstrated that the test statistics asymptotically follow an F-distribution with degrees of freedom 2 and T-$2p$ for $\omega \in (0, \pi)$. The time dimension associated with various frequency levels can be computed using the formula $T = 2\pi/\omega$. Ciner (2011) demonstrated that the presence of a causal link at frequencies of 2.5, 1.5, and 0.5 corresponds to short-, medium-, and long-term causality, respectively. In contrast, causality at frequencies below 0.1 indicates a permanent causality relationship.

While Bodart and Candelon (2009) demonstrated that the frequency-domain causality test performs particularly well when variables exhibit conditional heteroscedasticity, recent studies have shown that its results can vary significantly across different subsamples (Aye et al., 2017; Çevik et al., 2019; Warshaw, 2020). We account for this by employing a rolling-window estimation procedure to estimate the VAR model and applying the FDGC test to each subsample, thereby capturing the time-frequency connectedness between variables. For weekly data, we use an optimal rolling-window size of 104 observations, corresponding to two years.

3.2. Wavelet coherence analysis

The continuous wavelet transform of $x(t)$ is expressed as follows:

$$W_x(\tau, s) = \int_{-\infty}^{\infty} x(t)\widetilde{\psi}^*_{\tau,s}(t)dt, \tag{8}$$

where s represents the scaling factor, determining the wavelet's length, and τ is the translation parameter, indicating the wavelet's position in time. The function $\widetilde{\psi}^*_{\tau,s}(t)$ is the complex conjugate of the scaled and shifted mother wavelet $\psi(t)$, defined as follows:

$$\widetilde{\psi}^*_{\tau,s}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-\tau}{s}\right), s, \tau \in \mathbb{R}, s \neq 0. \tag{9}$$

We use the Morlet wavelet suggested by Goupillaud and Grossmann (1984) as the mother wavelet. The cross-wavelet transform (XWT) of two time-series $x(t)$ $y(t)$ is given by the following:

$$W_{xy}(\tau, s) = W_x(\tau, s)W^*_y(\tau, s). \tag{10}$$

The wavelet coherence between $x(t)$ and $y(t)$ is defined as follows:

$$R^2(\tau, s) = \frac{\left|S\left(s^{-1}W_{xy}(\tau, s)\right)\right|^2}{S\left(s^{-1}|W_x(\tau, s)|^2\right)S\left(s^{-1}|W_y(\tau, s)|^2\right)}, \tag{11}$$

where S is a smoothing parameter, and $0 \le R^2(\tau, s) \le 1$. The value of $R^2(\tau, s)$ measures the localized correlation between $x(t)$ and $y(t)$ in both the time and frequency domains. While wavelet coherence identifies comovement, it does not distinguish between positive and negative correlations.

Torrence and Compo (1998) addressed this using the following formula to determine the phase difference and identify positive or negative correlations:

$$\Phi_{xy}(\tau,s) = tan^{-1}\left(\frac{Im\{S(s^{-1}W_{xy}(\tau,s))\}}{Re\{S(s^{-1}W_{xy}(\tau,s))\}}\right). \tag{12}$$

Here, *Im* and *Re* denote the imaginary and real parts of the smoothed cross-wavelet transformation, respectively. The phase difference, $\Phi_{xy}(\tau, s)$, captures the oscillation delays between the two time-series.

In wavelet coherence graphs, black arrows indicate phase relationships. A zero phase difference signifies correlation. Arrows pointing to the right (left) indicate that the variables are in phase (out of phase), corresponding to positive (negative) correlations. An upward arrow implies that $x(t)$ leads $y(t)$, while a downward arrow suggests that $y(t)$ leads $x(t)$ by $\pi/2$. Various arrow positions represent different combinations of lead–lag relationships.

4. Data and empirical findings

This study investigates the relationship between carbon prices and the stock markets of emerging European countries. Carbon prices are represented by EUA futures, established as official emission allowances under the Kyoto Protocol in 2008. Each EUA grants the right to emit one ton of carbon dioxide or an equivalent amount of other greenhouse gases. The analysis examines the emerging EU countries of the Czech Republic, Greece, Hungary, and Poland.[1] All data are derived from Refinitiv Eikon.[2]

Fig. 1 illustrates the price series of EU carbon emission allowances, tracing the development of the EU ETS since its inception in 2005. The system has progressed through four distinct phases:

- **Phase I (2005–2007)**: A preparatory stage that adopts a "learning by doing" approach to set the groundwork for subsequent phases.
- **Phase II (2008–2012)**: Aligned with the first Kyoto Protocol commitment period, this phase introduced specific emission-reduction targets for participating countries.
- **Phase III (2013–2020)**: Marked by substantial system enhancements to address challenges identified in the earlier phases.
- **Phase IV (2021–2030)**: Builds on prior improvements, reinforcing the EU's dedication to reducing emissions and tackling climate change.

The results presented in Fig. 1 indicate that during Phase I (2005–2007), carbon prices fluctuated significantly, ranging from 0.1 to 35, reflecting the high volatility typical of a newly established market. This aligns with theoretical expectations, as this period was characterized as a "learning by doing" phase. Conversely, the carbon prices in-Phase II and, to a lesser extent, Phase III (2008–2017) are relatively stable, suggesting a maturing market. However, starting in 2017, during Phase III and continuing into the early period of Phase IV (2021–2023), carbon prices rose sharply, reaching record highs in 2022–2023. This trend illustrates the evolving dynamics of the carbon emissions market. One key contributing factor to the surge in carbon prices could be the updates to the EU ETS' market stability reserve (MSR) mechanism. Under the adjusted ETS auctioning regulation, the volume of allowances available for auction was revised during 2013–2020, with auction volumes reduced by 400, 300, and 200 million allowances in 2014, 2015, and 2016, respectively. To address the surplus of allowances, these backloaded capacities were withheld from auctions and transferred to the MSR, established in 2018 and operational in 2019. These regulatory updates and policy decisions in the EU ETS significantly influenced carbon price trends, driving both the direction and the magnitude of the fluctuations (European Commission, 2024).

Using weekly data, the dataset spans from January 2, 2008, to November 27, 2024,[3] and follows the methodology of Wen et al. (2020).[4] Logarithmic differences are applied to calculate return series, whereas realized variance is derived from the sum of squared daily returns. As shown in Table 1, the descriptive statistics reveal positive weekly mean returns for the EUA, in contrast to the negative mean returns for the stock markets in these countries. However, the standard deviation values indicate that EUA returns are the most volatile, whereas the Czech stock market exhibits the lowest volatility. All return series are negatively skewed and exhibit excess kurtosis, suggesting leptokurtic distributions with fatter tails and sharper peaks than a normal distribution. The unit root test results indicate that all return series are stationary at the level.

Fig. 2 displays the weekly return and variance series. The results indicate that the lowest weekly returns for EUA were recorded in 2013 and 2021, with the highest volatility also occurring in 2013. In contrast, stock markets experienced the most pronounced spikes in volatility during the global financial crisis (GFC) of 2008–2009 and the COVID-19 pandemic in 2020.

To implement the frequency-domain causality test, a bivariate VAR model is estimated using the return series of carbon and stock markets. The optimal lag lengths were selected based on the Akaike information criterion (AIC), which identified lags of 6, 4, 7, and 8 for the Czech Republic, Greece, Hungary, and Poland, respectively. Using these lag lengths, VAR models were estimated, and causality tests were conducted across different frequency bands.

Note that the results in Fig. 3 present the p-values for the calculated test statistics. A p-value less than 0.05 indicates the null hypothesis is rejected, suggesting a causal relationship between the variables. We present the analysis outcomes for the return series in Panel (a) of Fig. 3. Accordingly, the results for the Czech Republic reveal that we can reject the null hypothesis of no causality from carbon market returns to the Czech Republic's stock market returns at the 5% significance level within the frequency range [1.2, 1.7], corresponding to a cycle length of approximately 3–5 weeks. Conversely, in the frequency range [0, 1.2], corresponding to cycle lengths greater than 3 weeks, the Czech Republic's stock market returns were found to Granger-cause the carbon market. These results indicate a bidirectional causal link between the carbon market and stock returns in the Czech Republic. Although causality from the carbon market to the Czech Republic is evident only in the medium term, causality from the Czech Republic to the carbon market is observed in both the medium- and long-term cycles. The test results for the Greek stock market indicate a unidirectional causality relationship from the stock market to the carbon market. The null hypothesis of no causality was rejected at the 5% significance level within the frequency range [0.6, 1.1], corresponding to the cycle length of 5–10

[1] The emerging Europe stock markets are determined based on the MSCI classification. The Emerging Europe stock markets are determined based on the MSCI classification. According to MSCI, Greece, Czechia, Hungary, and Poland are classified as emerging markets and, therefore, are included in the analysis. Although several other EU ETS participant countries are classified as frontier markets by MSCI, they are excluded to maintain a homogeneous emerging-market sample.

[2] The Refinitiv codes for the Czech Republic, Greece, Hungary, and Poland stock indices are MSCZCHL, MSGREEL, MSHUNGL, and MSPLNDL, respectively. The Refinitiv code for carbon emission allowance prices is EEXEUAS.

[3] Given that the carbon market was newly established and not yet stable during the 2005–2007 period, the starting year for the data analysis has been set to 2008. Alberola et al. (2008) documented that carbon prices during Phase I were driven by institutional features—particularly the banking prohibition—and an oversupply of allowances, rather than market fundamentals, rendering this phase structurally distinct. Prior to 2008, carbon prices frequently took zero values, preventing the construction of logarithmic returns, and the sharp price surge at the end of Phase I introduced severe structural breaks and outliers. As shown by Bodart and Candelon (2009), such outliers reduce the power of frequency-domain causality tests. Therefore, following Koch et al. (2014), Phase I is excluded from the analysis.

[4] In the study, weekly instead of daily data were used to mitigate the impact of excessive noise typically found in daily data.

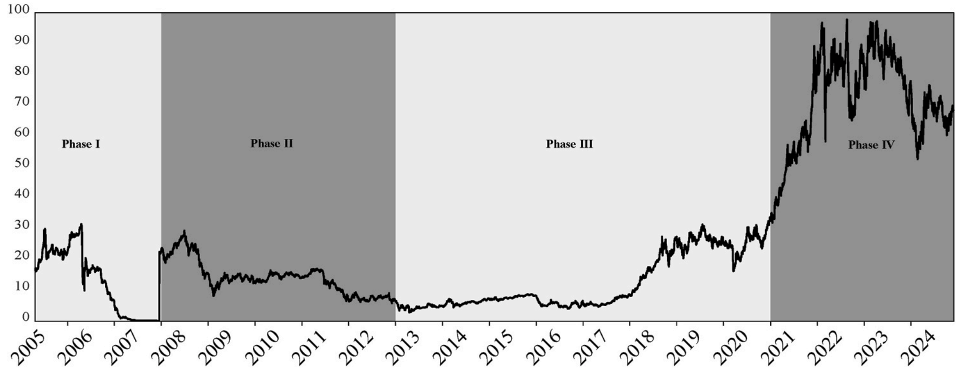

Fig. 1. EU carbon emissions allowance price.

Table 1
Descriptive statistics.

Return	EUA	Czechia	Greece	Hungary	Poland
Mean	0.128	−0.079	−0.413	−0.026	−0.113
Max	22.805	13.445	27.401	22.630	15.884
Min	−44.895	−34.763	−45.797	−33.962	−28.545
Std. Dev.	6.464	3.773	6.091	5.225	4.454
Skewness	−0.833	−1.533	−0.962	−1.386	−0.936
Kurtosis	8.705	14.323	9.070	12.074	7.406
Jarque-Bera	1299.784 [0.000]	5063.930 [0.000]	1492.228 [0.000]	3312.221 [0.000]	843.213 [0.000]
ADF	−8.349***	−12.703***	−15.785***	−11.416***	−7.362***
PP	−29.704***	−30.054***	−31.886***	−30.277***	−29.528***
KPSS	0.083***	0.020***	0.030***	0.036***	0.034***

Note: *** indicates stationarity at the 1% significance level.

weeks. This suggests a causal relationship between the two markets in the medium term. The test results for Hungary reveal that stock market returns Granger-cause carbon returns only in the long term. The null hypothesis of no causality was rejected at the 5% significance level within the frequency range [0.01, 0.5]. However, no causal relationship was identified between the carbon market and Hungary's stock market. The findings for Poland indicate that the stock returns Granger-cause EUA returns in the short, medium, and long terms. Furthermore, the carbon market is Granger-caused by the stock market within the frequency range [1.2, 1.7], corresponding to a cycle length of 3–5 weeks. This suggests that the causal relationship from EUA to stock returns occurs only in the medium term.

Panel (b) of Fig. 3 presents the causality test results for the realized variance series. We calculate test statistics using bivariate VAR models with a realized variance series. According to the AIC, the optimal lag length is 10 for all bivariate VAR models. The findings in Panel (b) of Fig. 3 show that, for the Czech Republic, there is no causal relationship between the volatility of carbon prices and the stock market. However, in the case of Greece, stock market volatility is identified as the Granger-cause of carbon price volatility within the frequency range [0.9, 1.1], corresponding to a cycle length of 5–7 weeks. In contrast, no volatility spillover from the carbon market to the Greek stock market was observed. A bidirectional causality relationship between the carbon market and the stock market exists in Hungary, with similar cyclical patterns. Specifically, volatility transmission from the stock index to the carbon index is present in the short, medium, and long term. In contrast, volatility spillover from the carbon to the stock index occurs only in the medium and long terms. In the case of Poland's stock market, the results show a unidirectional volatility spillover effect from the carbon market to the stock market, which is statistically significant in the medium and long terms.

Table 2 presents the results of the frequency-domain test, which reveal that, in terms of return series, the stock markets in Greece and Hungary are not influenced by the carbon market. In contrast, the stock markets of the Czech Republic and Poland are affected by the carbon market, but only in the medium term. However, given that causality from the stock market to the carbon market is observed across at least one frequency band in all countries, the causal relationship is greater in the opposite direction. This indicates that the price discovery process primarily flows from the stock index to the carbon index. Among the countries analyzed, the Polish stock index has the greatest influence on the carbon market, with causal relationships detected across short-, medium-, and long-term horizons.

Regarding volatility spillovers, only the Hungarian stock market is influenced by the carbon market across short-, medium-, and long-term horizons. The patterns observed for Hungary and Poland—both of which operate under carbon taxation regimes—are considered descriptive rather than evidence of a policy effect, as carbon taxation is not explicitly modeled in the analysis. However, the carbon market is affected by all stock markets in the medium term except for the Czech Republic, indicating that the direction of information flow between markets largely moves from the stock to the carbon index.

As noted earlier, the evolution of the carbon market has unfolded in distinct phases, suggesting that the relationship between the carbon and stock markets may vary across subsamples. Additionally, during the sample period, several financial and geopolitical crises—including the GFC, the European debt crisis, the COVID-19 pandemic, and the Russia–Ukraine war—potentially altered the relationships among the variables. To account for these dynamics, frequency-domain causality test statistics were computed for subsamples using a rolling-window approach, resulting in time-varying test outcomes. This method enables the examination of the evolving relationships between the carbon and stock markets across both temporal and frequency dimensions.

Fig. 4 illustrates the time-varying FDGC test results. Panel (a) presents the causal relationship between carbon and stock returns, and Panel (b) displays the results for the causality test of the realized variance. As shown in Fig. 4, the link between the carbon market and stock markets varies across subsamples. For instance, as indicated in Fig. 3, a

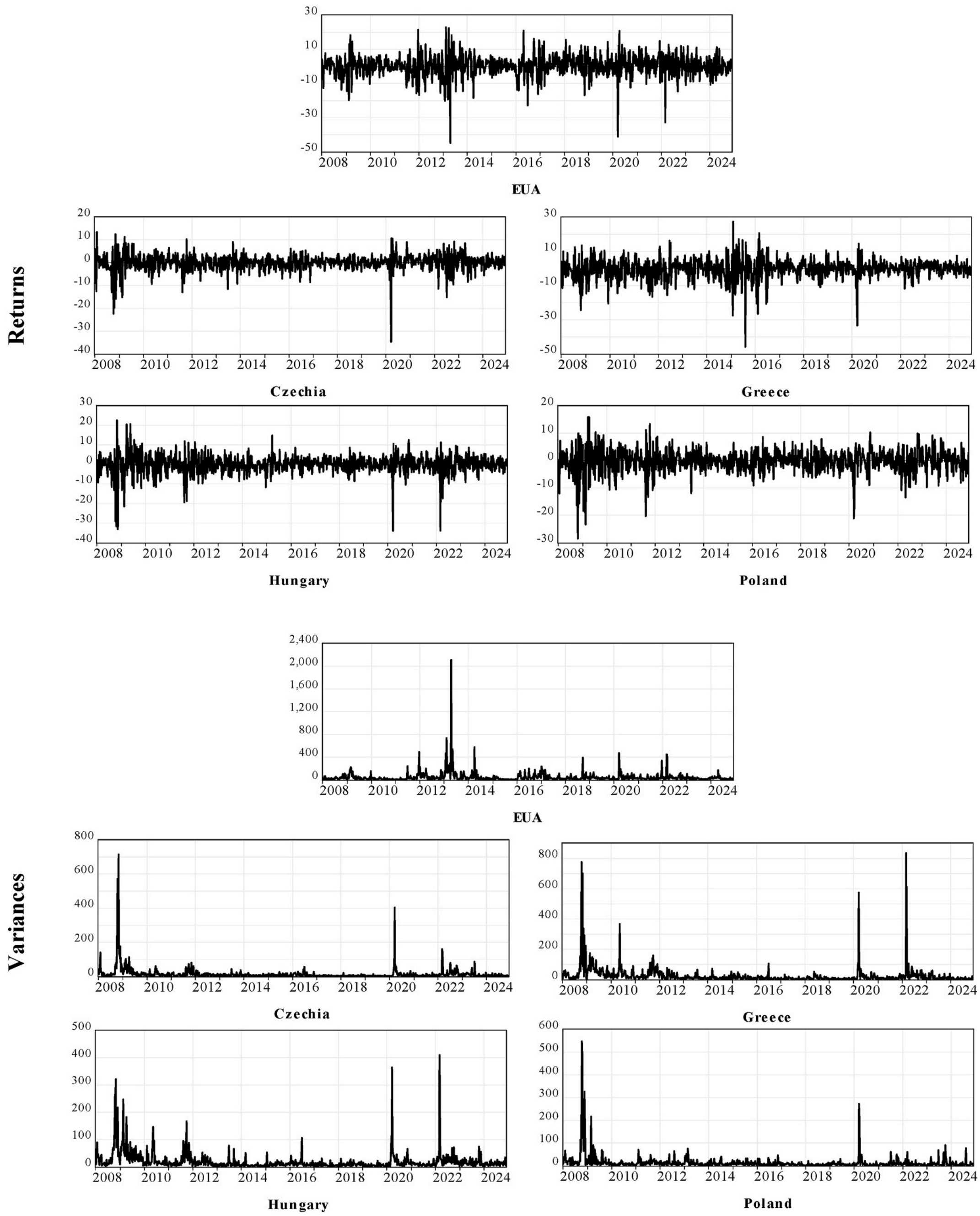

Fig. 2. Return and variance series.

causal relationship from carbon returns to Czech stock returns exists only in the medium term. However, Panel (a) of Fig. 4 shows that carbon returns are Granger-caused by Czech stock returns in the short term in 2010, 2011, 2012, and 2020. Furthermore, between 2011 and 2014, within the frequency range of [0.7, 1.7], at least a one-way causality relationship from the carbon market to the Czech stock market was identified. The time-varying test results for Greece highlight two notable subsample periods. In 2012, a causal relationship between the carbon index and the stock index was detected in the frequency range [1.3, 1.6]. Conversely, in 2021, a bidirectional long-term causality relationship was observed between the two markets. For Hungary, the findings indicate that at the beginning of the sample period, both short- and long-term causal effects ran from the carbon index to the stock index. Between 2017 and 2020, however, this causality was limited to the long term. From 2020 onward, the stock market is consistently Granger-caused by the carbon market, and, notably, a bidirectional causal relationship emerges in 2024. A similar pattern is observed for Poland, albeit with a shift in direction. Until 2020, causality relationships from the carbon index to the stock index were identified across various frequency ranges, yet after 2020, the causality direction reversed, with the stock market becoming the Granger-cause of the carbon market.

Panel (b) of Fig. 4 illustrates the time-varying causality test results for the variances of the variables. Although the results in Fig. 3 suggest no causal link between carbon and stock markets in the Czech Republic, Fig. 4 shows that causality relationships emerge across various subsample periods and frequency ranges. Specifically, volatility spillovers from the carbon market to the stock market are evident in specific periods (2010, 2011, 2013, 2014, 2019, 2022, 2023, and 2024). Furthermore, bidirectional causality in variance between the two markets was identified in 2012, 2014, 2016, 2021, 2022, and 2023, indicating

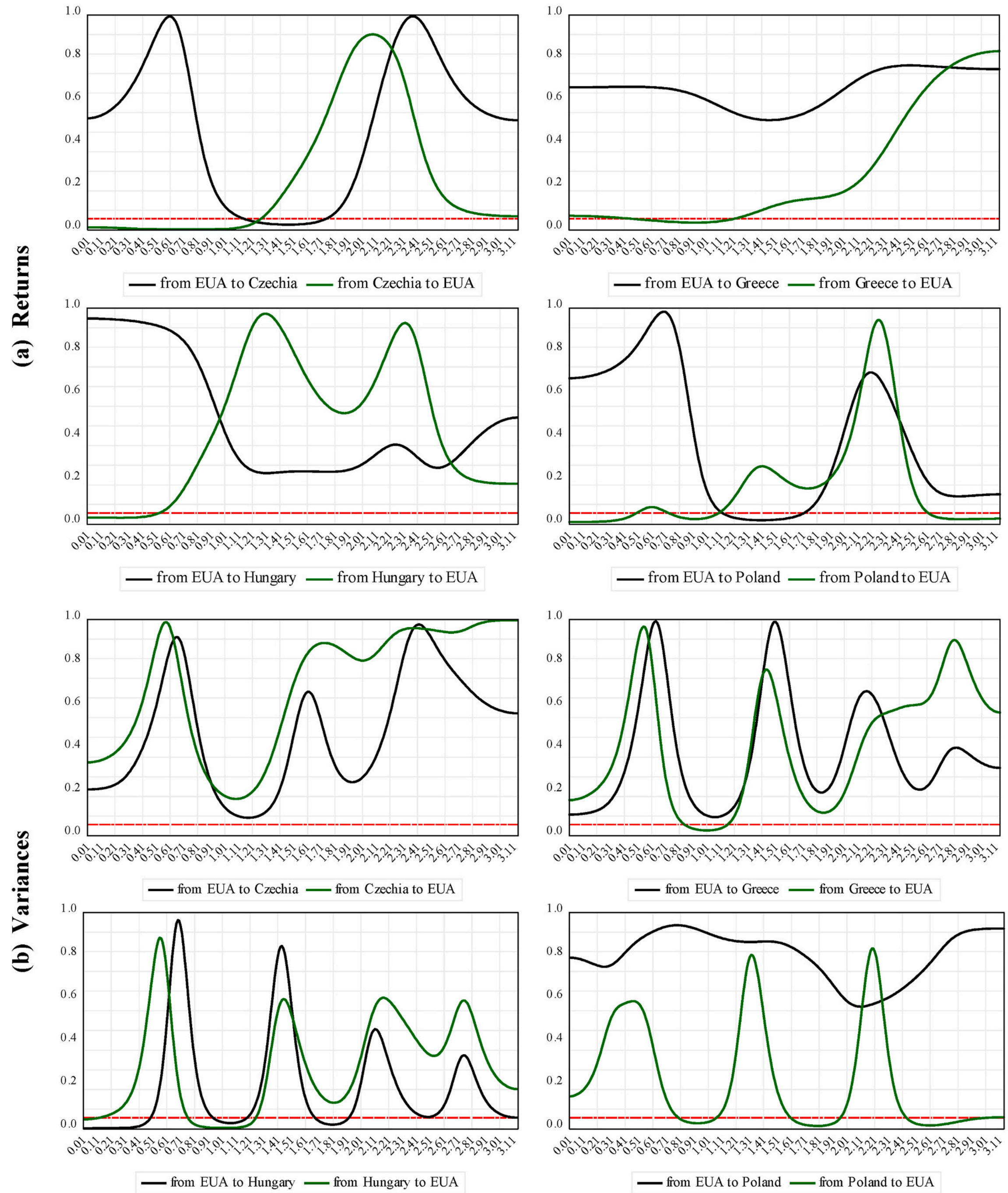

Fig. 3. Frequency-Domain Causality Test Results
Note: The dashed line represents the 5% significance level.

dynamic, evolving interactions over time. The findings for Greece indicate a notable increase in market integration after 2020. In 2010, a causal relationship from the carbon index to the stock index was identified within the frequency range [1.8, 2.1]. By 2012, this causality had shifted to the frequency range of [2.4, 2.6], suggesting evolving interactions. In 2015, evidence of both short- and long-term causal relationships between the stock index and the carbon index emerged. Starting in 2020, bidirectional causality relationships have been observed between the two markets across various frequency ranges, reflecting enhanced interdependence in recent years.

The results for Hungary also highlight dynamic patterns of causality over the study period. Until 2019, causality flowed primarily from the carbon index to the stock index. However, notable exceptions occurred in 2010, 2012, 2015, 2016, and 2018, in which causal relationships from the stock market to the carbon market were also identified. During these years, bidirectional causality emerged within specific frequency bands, indicating periods of mutual influence between the two markets. From 2020 onward, the relationship has intensified, with bidirectional causality becoming more pronounced, particularly at short-term frequencies, suggesting increased interconnectedness between the two markets.

The analysis results for Poland reveal that volatility spillovers from the stock market to the carbon market occurred during two distinct periods: 2013–2015 and 2018–2023. These episodes indicate periods in which stock market fluctuations significantly influenced volatility in the carbon market, suggesting heightened interconnectedness between the

Table 2
Summary of causality test results.

Causal link			Return			Variance		
			Long-term	Medium	Short-term	Long-term	Medium	Short-term
EUA	→	**Czechia**		✓				
EUA	→	**Greece**						
EUA	→	**Hungary**				✓	✓	✓
EUA	→	**Poland**		✓				
Czechia	→	**EUA**	✓	✓				
Greece	→	**EUA**		✓			✓	
Hungary	→	**EUA**	✓			✓	✓	
Poland	→	**EUA**	✓	✓	✓		✓	✓

Notes: We classify the long, medium, and short terms as the frequency bands [0.01, 0.5], [1.0, 1.5], and [2.5, 3.1], respectively.

two markets.

In summary, the results of the time-varying FDGC test reveal that the link between the carbon and stock indices is more pronounced at the beginning and end of the sample period. Notably, the significant increase in causal linkages observed from 2020 onward suggests heightened market integration in the wake of the COVID-19 pandemic. These findings are closely aligned with those reported by Qiu et al. (2023).

We also employ the wavelet coherence approach to investigate the link between the variables in time and frequency domains. Thus, the Morlet wavelet, developed by Goupillaud and Grossmann (1984) as the mother wavelet, is employed, with positive and negative correlations identified using the method by Torrence and Compo (1998).

Fig. 5 presents the wavelet coherence analysis results, where rightward arrows indicate an in-phase relationship (positive correlation) between the carbon and stock markets, and leftward arrows represent an out-of-phase relationship (negative correlation). Upward arrows indicate that the carbon index leads the stock index, whereas downward arrows indicate the reverse, with the stock market leading the carbon market. Additionally, upward-right arrows highlight a positive correlation in which the carbon market leads the stock market. In contrast, downward-left arrows indicate a negative correlation in which the stock market leads the carbon market. In the figure, black contours indicate statistically significant correlations at the 5% level, whereas the white line marks the cone of influence. The vertical axis in the figure represents the frequency range, with the 0–8 range corresponding to the short term, reflecting two months; the 8–32 range represents the medium term, spanning 2–8 months; and the 32–256 range captures the long-term relationship, spanning periods of more than eight months.

As shown in Fig. 5, the wavelet coherence analysis results for the Czech Republic demonstrate a positive relationship between the carbon market and the stock market, particularly in the medium and long term. During these periods, the stock market leads the carbon market, indicating that stock returns influence carbon returns. This interaction is statistically significant in the years 2009, 2013, 2017, and 2020. For Greece, the wavelet coherence analysis shows positive and statistically significant correlations in the short and medium terms. In 2011, the stock market led the carbon market, while in 2016, 2020–2021, and 2023, a same-direction link between the carbon and stock markets was identified. Similarly, for Hungary and Poland, the results show a positive relationship between the carbon and stock markets during the periods of 2016–2017, 2020–2021, and 2023. The volatility spillover results in Panel (b) of Fig. 5 demonstrate statistically significant and positive correlations for all countries after 2020. Except for Greece, the carbon market is influenced by the stock markets of all other countries.

5. Robustness checks

To assess the robustness of the results, the sample was divided into two subperiods—pre-Phase III and post-Phase III—and the FDGC analysis was reapplied to the return series. For each subperiod, bivariate VAR models were estimated, with the optimal lag length selected using AIC. Subsequently, the FDGC test was conducted, and the corresponding results are reported in Fig. 6.

As illustrated in Fig. 6, the findings are broadly consistent with the time-varying FDGC test outcomes presented in Fig. 4. Specifically, Fig. 6 reveals medium- and long-term causality from the EUA to the Czech stock returns both before and after 2013, a pattern that is likewise captured by the time-varying FDGC results in Fig. 4 for the same periods. In contrast, Fig. 6 shows no evidence of causality from the EUA to the Greek stock market in either subperiod, which is consistent with the restricted causality test results reported for Greece in Fig. 4. Similarly, for the Hungarian and Polish stock markets, the causality dynamics documented in Fig. 6 closely mirror those observed in Fig. 4.

Previous studies indicated that developments in the German stock market influence Central and Eastern European stock markets (Manolis et al., 2010; Syllignakis & Kouretas, 2010, 2011; Davidescu et al., 2023). Accordingly, to assess the robustness of the baseline results, the German stock market was incorporated as a control variable in the second-stage FDGC analysis. Specifically, the lagged values of German stock returns and volatility were included as control variables in the bivariate VAR models, and the causality tests were reestimated for both return and variance series. As shown in Fig. 7, the results are largely consistent with those presented in Fig. 3, indicating that the causal relationships are robust and not driven by spillovers from the German stock market.

6. Discussion

The frequency-domain and time-varying causality results offer deeper insights into how equity markets and the EU carbon market interact across distinct investment horizons. A central finding is that causality predominantly runs from stock markets to carbon prices, particularly in medium- and long-term frequency bands, and intensifies under market stress. This pattern suggests that equity markets act as a forward-looking aggregator of information about carbon prices rather than reacting to developments in the emissions market.

From an economic perspective, this result reflects that equity prices embed expectations about future economic activity, industrial output, energy demand, and regulatory conditions. When stock markets decline—especially during systemic events, such as the GFC, the COVID-19 pandemic, or the Russia–Ukraine conflict—investors revise expectations about production intensity, fossil-fuel usage, and energy consumption. These revisions lower expected demand for emission allowances, which subsequently affects carbon prices with a lag. Çevik et al. (2024) reported a similar result: equity markets exhibit predictive power over oil markets, particularly during downturns and adverse market conditions. The frequency-domain causality framework explicitly captures this mechanism: long-horizon causality from equities to carbon prices reflects persistent adjustments in expected emissions and regulatory pressure, rather than temporary market noise.

Consistent with the findings of Zhang et al. (2021), short-term spillovers occur predominantly during crisis periods and are concentrated in higher-frequency bands. These short-run dynamics likely reflect noise-driven dynamics associated with heightened uncertainty, liquidity shocks, speculative trading, and abrupt portfolio reallocations.

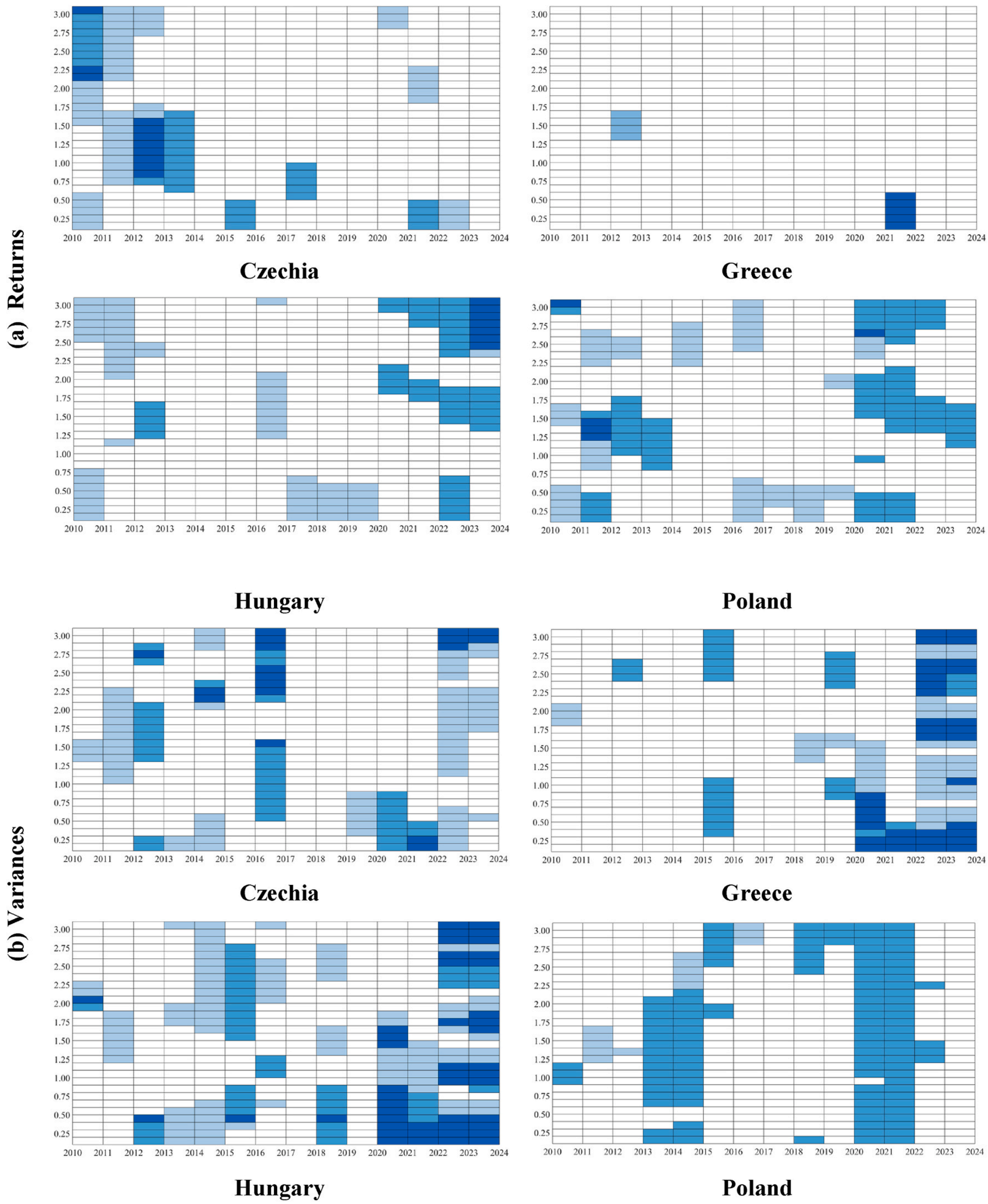

Fig. 4. Time-varying FDGC Test Results
Note: The causality relationship is determined based on a 5% significance level. White areas indicate no causality between EUA and the stock market. Light blue areas ( ) show causality from EUA to the stock market. Light steel blue areas ( ) suggest causality from the stock market to EUA, and dark steel blue areas ( ) indicate bidirectional causality.

During such episodes, equity and carbon markets respond simultaneously to common shocks, such as abrupt changes in energy prices or risk sentiment, creating transient spillovers that dissipate quickly. Importantly, the absence of persistent short-term causality during calm periods supports the view that these high-frequency effects are not structural but rather arise from market microstructure frictions and investor behavior.

The predictive content of equity-to-carbon causality has important implications. Because the FDGC test incorporates lagged dynamics, statistically significant causality implies that past equity-market movements contain information about future carbon price changes over specific horizons. For investors, this provides an early-signal mechanism: sustained downturns or recoveries in equity markets can be used to anticipate shifts in carbon prices, particularly at policy-relevant horizons.

From a policy perspective, the dominance of long-term causality from equity markets to carbon prices suggests caution in implementing reactive short-term regulatory interventions. During downturns, declining carbon prices may reflect reduced expectations about economic activity and emissions rather than regulatory failure. Conversely,

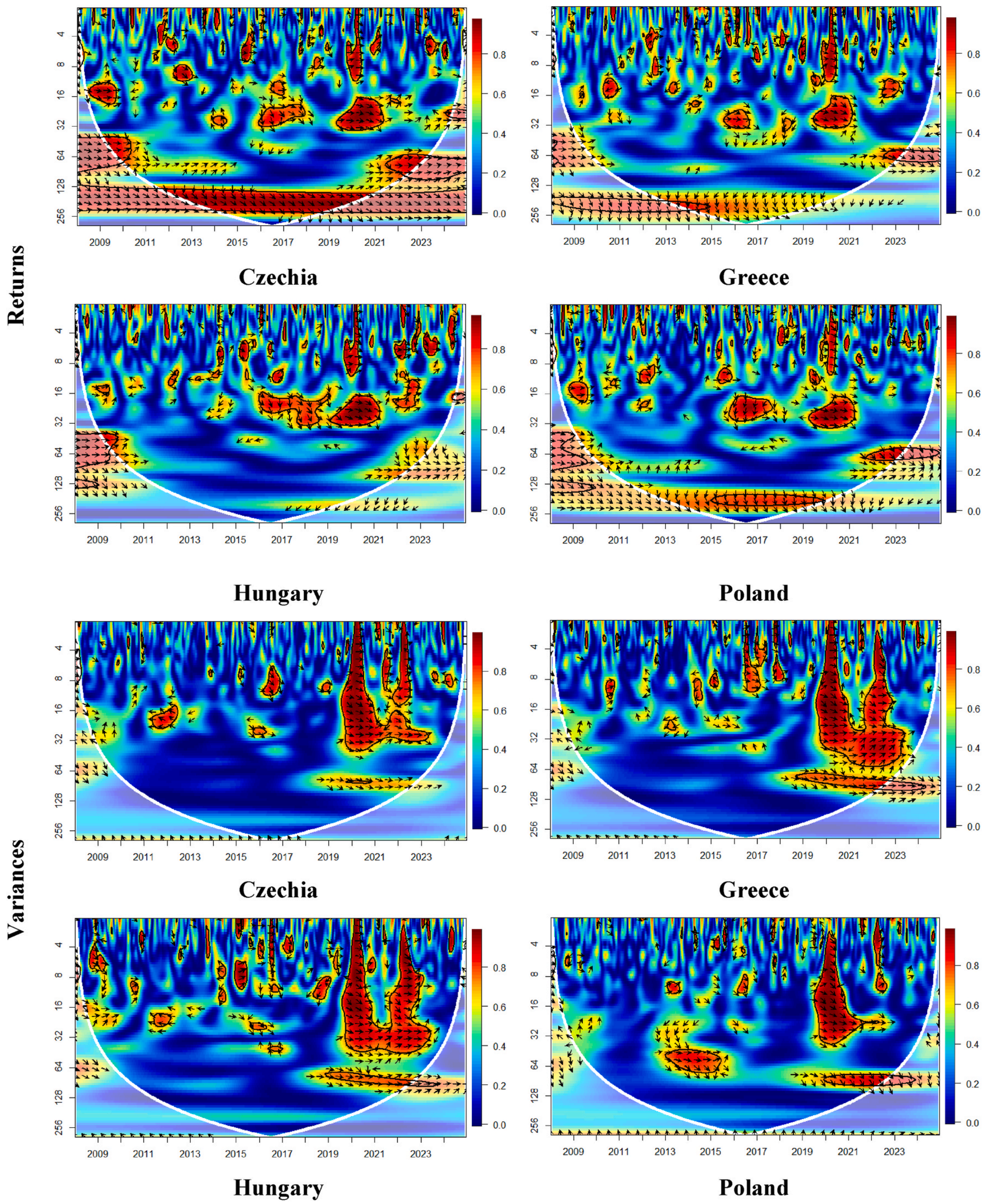

Fig. 5. Wavelet coherence analysis results.

sustained equity-market expansions may signal increasing future emissions pressure, suggesting periods when regulatory tightening—such as adjustments to allowance supply or related policy instruments—could become more relevant. These interpretations are indicative rather than prescriptive and suggest that aligning regulatory attention with long-horizon market signals, rather than short-term volatility, may improve policy coherence and credibility without directly evaluating specific policy tools.

Finally, the consistency of results across the Czech Republic, Greece, Hungary, and Poland supports their relevance for other Central and Eastern European economies. These countries share similar industrial structures, energy dependencies, and stages of sustainability transition, making the observed dynamics broadly representative of the region. The stronger equity-to-carbon spillovers observed in Poland and Hungary—particularly across multiple horizons—suggest that deeper financial markets amplify the transmission of economic expectations into carbon pricing.

7. Conclusion

7.1. Empirical findings

This study examines the dynamic relationships between the carbon market and stock markets across time and frequency domains. EUA

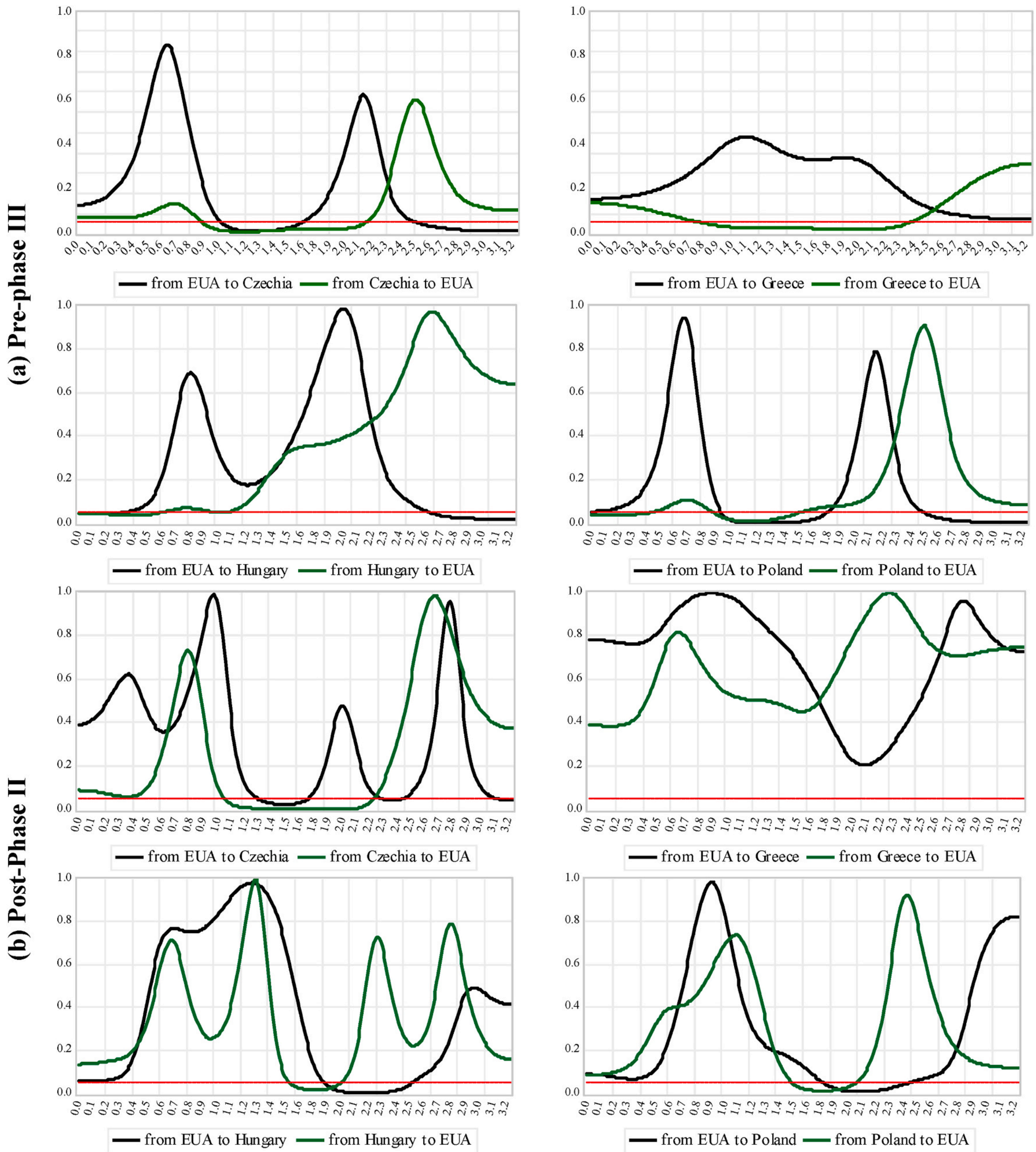

Fig. 6. Frequency-Domain Causality Test Results for Pre-Phase III and Post-Phase II
Note: The dashed line represents the 5% significance level.

carbon emission allowance futures prices are used as a proxy for carbon prices, and stock markets from emerging European countries are analyzed. According to the MSCI classification, emerging Europe includes the Czech Republic, Greece, Hungary, and Poland. While the literature has largely focused on stock markets in developed economies, this study addresses the comparatively underexplored context of emerging markets, filling an important gap in the literature. Our empirical findings are summarized as follows:

According to the full-sample FDGC test results, the stock markets in Greece and Hungary are not influenced by the carbon market. In contrast, those in the Czech Republic and Poland are affected, but only in the medium term. Evidence of causality from the stock market to the carbon market is observed across at least one frequency band for all countries, indicating that price discovery primarily flows from the stock index to the carbon index. Among the countries analyzed, the Polish stock market has the greatest influence on the carbon market, with causal relationships detected across short-, medium-, and long-term horizons. In terms of volatility spillovers, only the Hungarian stock market is influenced by the carbon market across all time horizons. The carbon market's volatility, however, is influenced by the volatility of all stock markets in the medium term, with the exception of the Czech Republic, indicating that the predominant direction of information flow runs from equity markets to the carbon market. The time-varying test results further demonstrate that the relationship between carbon and stock markets varies across subsamples. In particular, the connectedness between the carbon and stock indices is most pronounced at the beginning and toward the end of the sample period. Notably, the significant increase in causal linkages observed from 2020 onward points to intensified market integration following the COVID-19 pandemic. The wavelet coherence analysis corroborates these findings, confirming that the identified causal dynamics are not temporally uniform but vary across subsample periods, with the interaction between carbon and

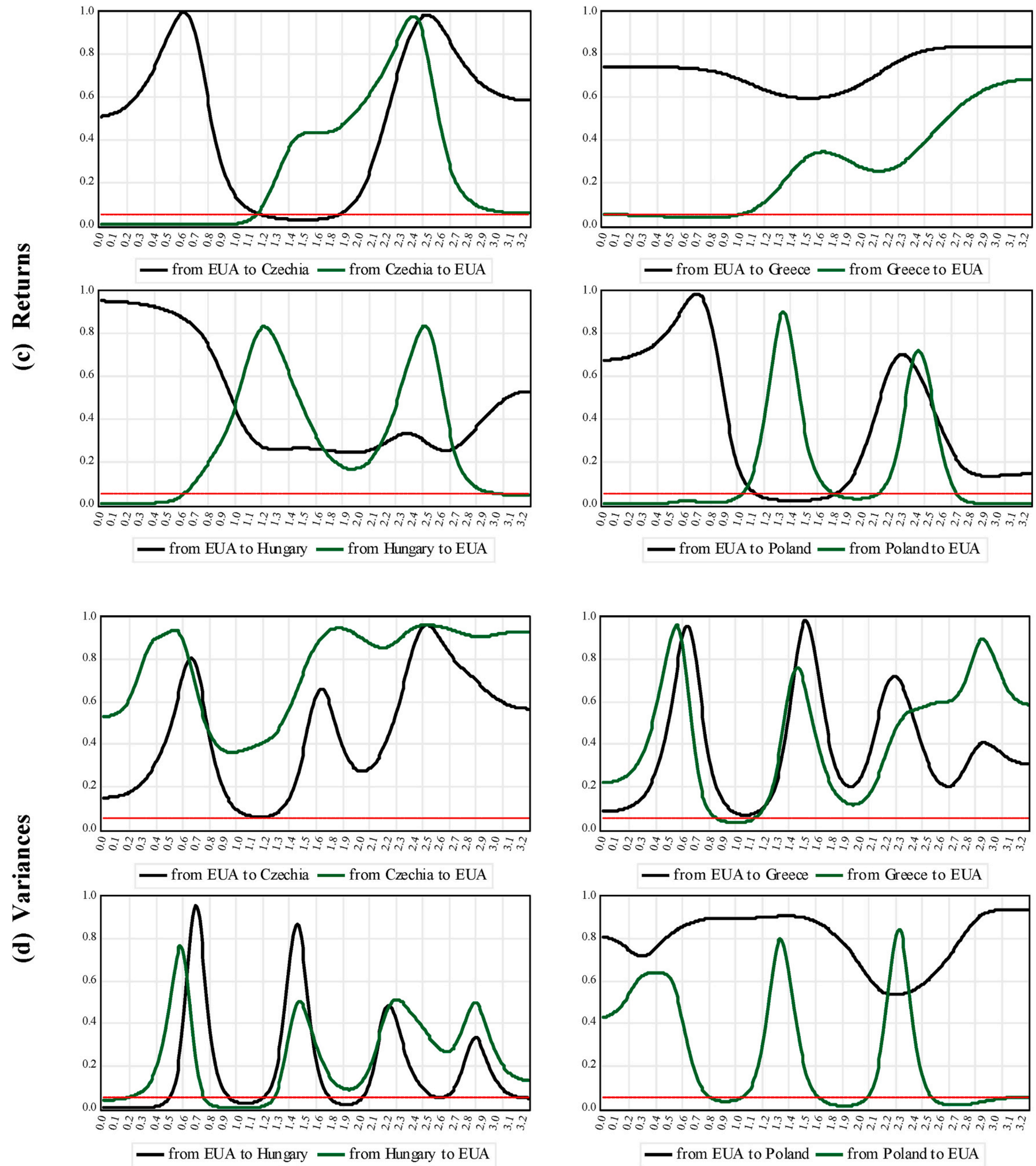

Fig. 7. Frequency-Domain Causality Test Results with the Control Variable
Note: The dashed line represents the 5% significance level.

stock markets intensifying after the onset of the pandemic.

The results of the frequency-domain causality and wavelet coherence analyses offer compelling insights. Across subsamples, the frequency-domain causality analysis shows that causal interactions between the variables intensify before 2010, particularly between 2008 and 2010, and after 2020, notably from 2020 to 2024. These patterns indicate that the relationship between carbon prices and equity markets strengthens during periods of significant market turbulence. The first phase, 2008–2010, coincided with the GFC, when industrial activity slowed and economic output contracted sharply in response to the recession and declining demand. A similar pattern emerged following the global pandemic. The relatively weaker evidence observed for 2016–2018 can also be attributed to Brexit and the trade war between the U.S. and China. During these periods, the sudden and severe decline in corporate free cash flow led to sharp drops in equity-market indices. Concurrently, the economic slowdown contributed to a substantial decrease in energy consumption, primarily driven by fossil fuels, as reflected in carbon prices.

Under such economic conditions, our findings indicate that the causal association between carbon and equity markets becomes stronger. This observation is consistent with our theoretical expectations. However, what is particularly striking is the relatively higher dominance and predictive power of equity markets over carbon markets during these economic phases. In contrast, the wavelet coherence methodology reveals stronger comovements between the variables during the periods between these economic disruptions, specifically from 2010 to 2020. During this time, carbon and equity markets are more closely aligned, highlighting their correlation. These findings indicate that the correlation and causality dynamics between stock and carbon markets vary across economic phases, strengthening during particular periods.

7.2. Policy implications

Our empirical findings that equity markets Granger-cause carbon prices across multiple frequency bands hold concrete policy implications for central banks, financial regulators, and energy policymakers. As our results indicate, equity markets provide a cost-efficient platform for monitoring carbon price risk, as their high liquidity and established infrastructure allow macroeconomic conditions, firm-level expectations, regulatory outlooks, and global risk sentiment to be continuously incorporated into prices at minimal marginal cost. Therefore, central banks and supervisory authorities can employ equity-based signals as a forward-looking monitoring tool, complementing traditional carbon market indicators, which are often policy-driven and slow to adjust. Given our findings, such signals can be embedded in macrofinancial surveillance frameworks and climate stress-testing exercises to anticipate shifts in carbon price risk.

Consistent with our empirical results, the predictive role of equity markets carries important implications for clean and carbon-intensive energy policies. Because equity prices rapidly incorporate expectations about regulations, energy demand, and sectoral profitability, their ability to signal future carbon price movements reflects anticipated reallocations between fossil-fuel-based and clean-energy systems. Our findings show that rising equity-based carbon price signals can alert policymakers to rising cost pressures on carbon-intensive activities, allowing earlier adjustments to clean-energy subsidies, investment incentives, and infrastructure planning. In contrast, weaker signals may caution against premature policy relaxation. The stronger predictive link observed during periods of market turbulence is particularly relevant, as our results demonstrate that crises intensify information transmission, making early signals critical for maintaining policy credibility.

From an investor perspective, our findings indicate that equity markets' ability to anticipate carbon price movements over medium- and long-term horizons provides valuable information for portfolio allocation and risk management. Investors can leverage equity-based carbon signals to adjust sectoral exposures between carbon-intensive and clean-energy firms, improve entry and exit timing, and strengthen hedging strategies against carbon price risk. The stronger predictive relationships observed during periods of market stress further suggest that equity signals are particularly informative for downside risk management, supporting their relevance in climate-aware investment strategies, stress testing, and ESG portfolio construction.

Finally, a descriptive comparison of countries with (Hungary and Poland) and without carbon taxes (Greece and the Czech Republic) does not demonstrate an explicit differentiation in equity–carbon market interactions. Because carbon taxation is not explicitly modeled, this observation should be interpreted as indicative rather than causal. The lack of a definitive distinction may be due to current tax schemes not yet being sufficiently strong or credible to produce detectable differences in sampling-based analyses. Stronger and more transparent carbon tax regimes could potentially enhance cross-country differentiation in equity–carbon linkages in future research that explicitly incorporates policy variables.

Author contributions

Emrah I. Cevik: Conceptualization, Literature Review, Methodology, Empirical Analysis, interpretation of results Samet Gunay: Introduction, Literature Review, interpretation of results Dániel Havran: Introduction, Literature Review, Conceptualization.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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