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Asymmetric connectedness among regional green economies, carbon markets, and oil shocks

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ABSTRACT

This study investigates spillovers among the US, Europe, and Asia green economies, carbon allowances and oil price shocks in 2010–2023. We segregate oil shocks in demand-, supply-, and risk-driven price movements. The TVP-VAR methodology is applied to model the dynamic interrelationships among the markets. Our static connectedness outcomes highlight a substantial role of the US and European green economy and the demand-driven shocks as emitters of innovations to other markets. It is found that European green economy is the main innovations contributor to global carbon allowances whereas the demand-driven oil shocks dominate in transmitting spillovers to others. We demonstrate that major economic events make connectedness increase. Our asymmetry analysis reveals a heightened susceptibility of the system to negative news, with the impacts of negative spillovers overcoming those of positive ones. The dynamics of spillovers emphasize how crucial it is to take into account both the time and the sign. Our research advances understanding of the complex relationships within the green-carbon-oil-shocks system. The results are potentially useful for risk managers and investors, as they allow the creation of effective risk management plans.

1. Introduction

Fostering green economy while enhancing the carbon allowance trading and controlling for the shocks coming from the crude oil market could help to efficiently decrease emissions of greenhouse gases (Gubareva et al., 2023a; Hanif et al., 2023; Esparcia & Gubareva, 2024; Ghosh et al., 2023a). With this aim, it is highly desirable to investigate the dynamic connectedness and spillovers within the green-carbon-oil-shocks system and provide a holistic perspective on their time-varying linkages contingent on distinct market states. It is especially important as economic, financial, disease-driven, and other crises could drastically affect connectedness within the system (Bossman et al., 2023a; Gubareva et al., 2023b, 2025; Hanif et al., 2025; Mensi et al., 2025; Patel et al., 2024; Umar et al., 2024; Umar and Gubareva, 2020, 2021; Yousaf et al., 2022). Moreover, it is well documented in previous studies that oil shocks

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could play the role of important contributors of exogenous innovations to diverse markets, thus justifying the inclusion of the oil shocks in our green-carbon-oil-shocks network (Aziz et al., 2022; Bossman et al., 2023a; Ready, 2018; Umar et al., 2021a, 2024; Yousaf, Arfaoui, & Gubareva, 2023).

In the current times of acute climate changes and increasing environmental consciousness the reduction of carbon emissions is extremely important to curb the global increase in temperature (Ghosh et al., 2023, 2024; Gubareva & Gomes, 2019). Therefore, an investment focus is migrated from carbon-intensive industries to low-carbon sectors, and such strategies become important tools for addressing climate change and carbon emission reductions (Madaleno et al., 2022). Furthermore, renewable energies provide valuable contributions to diminution of carbon and other greenhouse gases emissions as well as to sustainable development (Kocaarslan & Soytas, 2021). In what concerns the concerted action of several states, the European Union Emissions Trading System (EU ETS) has become a foundation stone of the EU's policies to withstand climate change challenges and nowadays represents the main cost-effective instrument for diminishing emissions of greenhouse gases (Dechezleprêtre et al., 2023). EU ETS is the first internationally established carbon market and remains the largest marketplace for carbon allowances trading on the global scale (Lynch & O'Hagan-Luff, 2024). EU ETS represents so-called 'cap and trade' system. It requires polluters to pay for their emissions, allowing to diminish emissions of greenhouse gases and producing income to support the EU's green transition (Ghosh et al., 2023, 2024). The developed under EU ETS carbon allowance trading strategy is regarded as a powerful tool for carbon emission reduction (Woerdman & van Zeben, 2023).

Regarding the green economy, during recent times, the green economy conception has been considered as a powerful mean for ensuring sustainable development in developed and emerging markets (Houssam et al., 2023). This explains the continuously increasing attention of the research community towards low-carbon economy indicating a path to an economic sustainability within the green economy paradigm (Zhu et al., 2023). The 2030 Agenda for Sustainable Development was established by the United Nations in 2015, which represents the outcome of concerted efforts by many nations around the globe to install a novel model for global development, aiming at reducing poverty, promoting well-being, curbing climate change, and protecting environment (Mishra et al., 2023). There are seventeen sustainable development goals in the UN Agenda for Sustainable Development. The UN's ratification of this Agenda has further sparked a global upsurge in interest in the green economy among scholars, leading to an impressive strand of literature on the subject, with Asian and European scholars leading green economy research. In the attempts to withstand climate change challenges, future studies are expected to be focused on creating a green economic system allowing for sustainable growth on the planetary scale (Mishra et al., 2023).

Having succinctly discussed the carbon allowances and the green economy, it is reasonable to suppose that there exist important linkages between the green economy and the carbon allowances, which could represent asymmetric patterns due to the complexity of the involved markets. Previously the connectedness and spillovers between these two markets have been mainly addressed through the prism of the pairwise relations within the binary green-carbon framework (Ashfaq et al., 2024; Li & Haneklaus, 2022; Reboredo et al., 2022). Yet, the strand of the literature that analyzes the green-carbon markets within a larger network comprising other asset classes is limited and scant, with rather scarce exceptions (Dai et al., 2023; Jahanger et al., 2023). Therefore, our principal motivation is to explore the joint behavior of green-carbon tandem within a larger system, i.e., being subject to endogenous influence from the crude oil market. In this manner, we contribute to advancing the knowledge frontier on interconnectedness of green economy, carbon allowances market, and oil shocks, which is potentially useful for reducing the greenhouse gases emissions. It is especially so as previous research has provided empirical evidence that green finance is a foundational cornerstone in the transition of carbon-intensive sectors to the green economy model, and that the mechanisms for carbon allowances pricing could efficiently stimulate community backing for clean technology initiatives and direct investments into sustainable development and green economy projects (Chatziantoniou et al., 2022). Thus, we provide a larger knowledge on complex dynamic connectedness within green economy, carbon and oil shocks framework resorting to an advanced econometric modeling framework, namely, TVP-VAR technique, in order to fill the identified void in the contemporaneous state of the art.

Notably, during the recent decade diverse crises, such as the pandemic, and financial turmoil caused by distinct geopolitical tensions have been adversely impacting the worldwide economy, exacerbating contagion risks across capital markets (Gubareva, 2021; Umar et al., 2021a, 2021b, 2021c, Umar, Manel, et al., 2021; Gubareva et al., 2022, 2023c, 2023d; He et al., 2022; Ali et al., 2024a, 2024b). Moreover, elevated uncertainty of capital markets represents a potential source of macroeconomic changes and, henceforth, may results in crystallization of risks not portrayed through the volatility dimension (Bloom, 2009; Bossman et al., 2023b; Huang et al., 2024; Mensi et al., 2023; Naveed et al., 2024; Yousaf et al., 2023a, 2023b). Thus, in recent times the issues of possible preventing systemic events transversal to capital markets have gained much importance. Therefore, interlinkages between different financial markets should be duly taken into consideration while designing portfolio allocation and hedge strategies, as cross-asset connectedness may play an important role in downside risk transmission.

It is also worth noting that elevated uncertainty in financial markets could be exacerbated by inherent instability of oil prices (Aziz et al., 2022; Balcilar et al., 2021; Bossman et al., 2023a; Dai et al., 2023; Jahanger et al., 2023; Mensi et al., 2023; Ready, 2018; Umar et al., 2024; Wang et al., 2022). Drastic shifts in the crude oil prices produce profound effects on capital markets, bringing about incessant riskiness and uncertainty (Ji & Zhang, 2019; Umar, Gubareva, et al., 2021; Wei et al., 2023; Yousaf, 2023a, 2023b; Zheng et al., 2023). Previous research provides empirical evidence that capital market uncertainty is amplified by volatility of crude oil prices. Certain analyses have demonstrated that implied volatility may help assessing the oil-driven downside risk and uncertainty with great precision (Umar, Gubareva, et al., 2022). Other authors report that oil volatility, proxied by the OVX index helps investors to better comprehend contagion risks effect between energy-based markets (Mensi et al., 2023; Çelik et al., 2022). In parallel, several studies segregated the oil price shocks in demand-, supply, and risk-driven innovations, following the original methodology proposed by Ready (2018); see Umar, Gubareva, et al. (2021), Aziz et al. (2022), Umar, Gubareva, et al. (2022), Umar et al. (2024). We resort to this methodology in our paper as it allows for a more meaningful analysis and a more accurate interpretation of the results.

From a theoretical standpoint, investigating the interplay among oil shocks, green economy indices, and carbon markets allows us to extend the understanding of interconnected asset systems within the broader context of environmental finance. This contributes to bridging fragmented research silos across energy economics, financial risk transmission, and low-carbon investment strategies. Practically, as economies pivot toward sustainable transitions and as energy markets face recurring geopolitical and macroeconomic shocks, comprehending these cross-market dynamics becomes critical. Our study provides investors, policymakers, and risk managers with actionable insights into how market segments central to the climate transition interact and respond asymmetrically to external shocks – facilitating more informed decision-making in both financial planning and environmental policy design.

Furthermore, there exists a noticeable gap in the literature concerning how disaggregated oil shocks influence the time-varying connectedness between green economy indices and carbon markets, particularly regarding the inherent asymmetries of these interrelationships. Exploring such dynamic and directional linkages offers valuable insights into the structure and evolution of systemic spillovers under varying economic and market regimes. Motivated by this gap, our study focuses on modeling pairwise time-varying interdependencies among these markets, accounting for the heterogeneous nature of oil shocks and the state-dependent magnitude of their impact. To this end, we employ the TVP-VAR methodology, which is well-suited for capturing both mean-based and extreme tail spillovers. This is crucial for understanding connectedness during turbulent market phases, such as bull and bear periods, where nonlinear dynamics often prevail (Ali, Umar, et al., 2024; Ghosh et al., 2023; Mensi et al., 2023).

This study offers several novel contributions to the literature on environmental finance and cross-market connectedness. First, we develop a unified analytical framework that jointly models the interactions among regional green economies (Asia, form Europe, and U.S.), EU allowances or carbon credits, and disaggregated oil price shocks (demand-, supply-, and risk-driven innovations). To the best of our knowledge, such comprehensive network has not been previously studied in a duly integrated form, i.e. considering endogenous influence from the crude oil market. Second, we introduce an asymmetry dimension to the TVP-VAR connectedness analysis, revealing distinct transmission mechanisms for positive versus negative shocks. This feature represents an underexplored facet, mostly overlooked in prior studies addressing green economy, carbon allowances, and oil shocks. Third, we analyze the evolution of spillovers in response to major global disruptions such as the European sovereign debt crisis, the COVID-19 pandemic, and the Russia-Ukraine conflict, offering new insights into the sensitivity and systemic responses of environmental and energy-linked markets. Fourth, we map pairwise spillovers to identify the structural roles of each component as net transmitters or receivers of shocks, and document that carbon allowance markets consistently act as net receivers. Finally, the study provides actionable insights for policy and investment strategy by highlighting the dominant role of demand-driven oil shocks and the asymmetry in shock transmission, particularly during crisis periods. These contributions collectively advance the theoretical and practical understanding of the interconnected system, comprising green economies, carbon markets, and oil shocks, subject to real-world complexities.

Our empirical analysis yields several noteworthy findings. The static connectedness results indicate that the U.S. and European green economy indices, along with demand-driven oil shocks, act as primary transmitters of innovations across markets. Among them, European green indices exhibit strong spillover effects, particularly influencing global carbon allowance prices. The Total Connectedness Index (TCI) reveals that approximately 38 % of the total forecast error variance is explained by cross-market spillovers, with this share rising significantly during major economic disruptions such as the COVID-19 pandemic. The dynamic analysis confirms that systemic connectedness intensifies during periods of market stress. Furthermore, the asymmetry assessment shows that negative return regimes amplify spillover transmission more than positive ones. Directional and pairwise connectedness results reinforce these patterns, revealing that the EU Allowances (carbon credit) market and Asian green markets consistently function as a net receiver of shocks, whereas demand shocks and European green markets predominantly act as persistent net transmitters.

The rest of the manuscript is organized as follows. The literature review on the most recent works is presented in Section 2. The data and econometric modeling framework are presented in Section 3. The empirical results and their discussion are provided in Sections 4 and 5, respectively. Section 6 concludes and provides a set of recommendations.

2. Literature review

The accelerating global agenda on sustainability, climate risk mitigation, and clean energy transition has heightened academic interest in understanding the interconnected dynamics among green economy assets, carbon allowance markets, and oil price shocks. Given the pivotal role of the EU Emissions Trading System (EU ETS) as a market-based mechanism for reducing carbon emissions, considerable research has focused on the interactions between carbon allowances and traditional energy markets, particularly oil (Ren et al., 2022). Additionally, due to the policy-sensitive nature of carbon pricing, a growing number of studies have examined the determinants of carbon allowance prices under evolving regulatory and economic conditions (Ghosh et al., 2024 and references therein). Despite this progress, an integrated understanding of how green economy indices, carbon markets, and oil shocks interact remains underdeveloped, especially subject to dynamic and asymmetric scenarios. To situate our contribution within this broader academic landscape, we organize the literature into four thematic strands: (i) oil shocks and carbon markets; (ii) oil shocks and green or clean energy sectors; (iii) carbon-green economy dynamics; and (iv) integrated multi-market connectedness studies.

2.1. Oil shocks and carbon markets

A well-established strand of literature examines how different types of oil price shocks, namely, demand-driven, supply-driven, and risk-based, affect the behavior of carbon markets. Zheng, Yin, et al. (2021) utilize quantile regression on data from 2008 to 2020 to assess the impact of oil innovations on EU carbon allowance prices. Their findings indicate that supply and demand shocks generally exert positive effects, whereas risk shocks negatively influence carbon returns, particularly under bearish market conditions.

Building on this, Zheng, Zhou, and Wen (2021) explore the Chinese carbon market from 2013 to 2020 using a nonlinear ARDL framework. They identify long-term asymmetric effects from oil shocks, with supply-driven innovations becoming increasingly influential following the institutionalization of China's national carbon market in 2017. The study underscores that the impact of oil shocks varies both by shock type and over time, suggesting evolving sensitivity of carbon pricing mechanisms to exogenous energy market dynamics.

Ren et al. (2022) extend this investigation by employing a quantile coherency approach to analyze tail dependencies in the EU ETS from 2014 to 2021. Their analysis reveals significant asymmetries in the oil-carbon linkage across investment horizons, with varying implications depending on the shock origin. The findings demonstrate that the efficiency of the carbon market is not static, but contingent on both the nature of oil shocks and prevailing market conditions. This highlights the importance of modeling such relationships using tools capable of capturing nonlinear and state-dependent behavior.

Collectively, these studies provide robust evidence that oil shocks serve as exogenous influencers in carbon market dynamics. However, previous studies often examine these interactions in isolation, lacking integration with broader financial and environmental systems, such as the green economy. This gap underlines the need for a more comprehensive, multi-market analytical framework, such as the one we adopt in this study.

2.2. Oil shocks and green economy dynamics

A growing segment of the literature explores how oil price volatility interacts with green financial instruments and clean energy markets. These studies provide valuable insights into the systemic vulnerabilities and transmission channels between traditional energy markets and low-carbon investments, particularly under conditions of economic uncertainty or financial distress.

Wang et al. (2022) investigate the time-varying causality among oil volatility, economic policy uncertainty, and a suite of green assets including green bonds, carbon allowances, and renewable energy indices. Using a non-parametric causality-in-quantile framework, their findings reveal that these relationships are highly state-dependent and asymmetric, intensifying during periods of market turbulence such as the COVID-19 pandemic. Notably, they demonstrate that oil price volatility and policy uncertainty function as significant predictors of cross-asset correlations, thereby shaping the comovement structures across environmentally sensitive markets. These results underscore the importance of accounting for exogenous volatility spillovers when modeling green asset behavior.

Complementing this, Dai et al. (2023) examine extreme risk spillovers across high-carbon stocks, green bonds, and crude oil using a quantile-based TVP-VAR model. Their findings suggest that the total spillover index peaks during tail events, reaching up to 83 %, while being more subdued at the conditional median. This reinforces the idea that extreme market states disproportionately influence systemic connectedness. Additionally, their analysis reveals a directional asymmetry: at the tails, green bonds and oil tend to act as net receivers of shocks, whereas other sectors emerge as shock emitters. This directional nuances, particularly evident during crises like the European sovereign debt crisis, highlight the need to consider asymmetries in risk contagion across asset classes.

Further emphasizing the environmental dimension, Jahanger et al. (2023) focus on the interaction between oil prices, renewable energy use, and carbon emissions in China's transportation sector. Using a bootstrap ARDL model, they find that higher oil prices contribute to a reduction in emissions both in the short and long term, while increased reliance on clean energy further amplifies this effect. Their results suggest that energy substitution, stimulated by oil price fluctuations, can play a meaningful role in emission mitigation. This study bridges the gap between macro-level energy market dynamics and micro-level environmental outcomes, offering practical implications for policymakers seeking to align fiscal strategies with sustainability goals.

Together, these studies demonstrate that oil market fluctuations exert profound, often nonlinear effects on green finance and clean energy sectors. However, most contributions isolate bilateral relationships and fall short of analyzing these interactions within a broader multi-market system. Moreover, few studies examine the directional nature of these spillovers, focusing on how their intensity evolves over time and across market regimes. Our study builds upon these insights by integrating oil shocks into a comprehensive, asymmetric, and time-varying connectedness framework that includes green economy indices and carbon markets, thereby filling a critical gap in the literature.

2.3. Carbon – green market interactions

A third stream of the literature explores the interconnected dynamics between carbon markets and green economy investments. These studies typically investigate how regulatory signals, financial innovation, and clean energy policies influence the relationship between carbon allowances and environmentally aligned assets, highlighting both direct financial spillovers and broader policy implications.

Liang and Qamruzzaman (2022) examine the structural determinants of green economy transitions in the BRIC nations from 1991 to 2018. Utilizing fully modified and dynamic least squares methods within a cointegration framework, they find that economic policy uncertainty and climate change exert statistically significant negative impacts on green economic development, whereas knowledge spillovers contribute positively. Their results stress the importance of mitigating policy uncertainty and fostering knowledge exchange in designing effective green transition strategies for emerging economies.

Building on the risk transmission dimension, Cao and Xie (2023) apply an extended quantile joint connectedness model to study spillovers between carbon allowances, fossil fuels, and renewable energy markets (2010–2022). Their findings suggest that tail events strengthen inter-market linkages, with more intense spillovers during extreme conditions. While renewable energies may offer diversification benefits for carbon portfolios, their hedging performance is shown to be highly state-dependent, necessitating nuanced risk management approaches.

Ha (2023) adopts a multivariate wavelet framework to explore the dynamic interaction between carbon risk and renewable energies. The study reveals persistent low-frequency coherency between carbon emissions and renewable assets during 2020–2022, particularly between the geothermal, solar, and biofuel sectors. The author also reports on high-frequency co-movements emerging in early 2022. Notably, the S&P green bond index shows anti-phase dynamics with carbon risk, whereas the S&P clean energy index is in phase with carbon emission futures, indicating their diverging roles in environmental financial systems.

Extending this inquiry, Ha et al. (2024) utilize TVP-VAR models to assess time-varying volatility connectedness among carbon, green bonds, renewable energies, and oil markets. The analysis shows that green and renewable energy assets often act as net emitters of shocks, while carbon emission futures alternate between being net transmitters and receivers depending on market phases—most prominently during the COVID-19 pandemic. The study also finds that oil markets consistently transmit shocks to carbon prices, reinforcing the interconnectedness of environmental and traditional energy markets.

Collectively, these studies emphasize the increasing financial integration between carbon markets and green economy instruments. However, most existing research either neglects the explicit role of disaggregated oil shocks or treats them as external rather than endogenous components of the green-carbon ecosystem. Our study addresses this shortfall by embedding disaggregated oil innovations within a unified, time-varying, asymmetric spillover framework involving regional green economies, and carbon allowance markets, thus advancing the current state of knowledge on environmental financial interdependencies.

2.4. *Integrated multi-market connectedness approaches*

While the interconnected dynamics among green economy indices, carbon allowances, and oil shocks have been explored in pairs, only a limited set of studies has attempted to examine these markets within an integrated systemic framework. This emerging strand of literature acknowledges the need for a holistic perspective, particularly under conditions of macroeconomic and environmental volatility. Wei et al. (2023) offer one of the few comprehensive assessments by investigating the total and time-frequency connectedness across carbon allowances, clean energy markets, oil prices, and climate oscillations from 2005 to 2021. Using a TVP-VAR-based time-frequency connectedness framework, they report substantial heterogeneity in spillover intensity across investment horizons. While average total connectedness is moderate, ranging from 8 % to 30 %, the total connectedness peaks during systemic crises such as the 2007–2008 Global Financial Crisis and the COVID-19 pandemic. Their findings underscore the predominance of climate oscillations as innovation transmitters and highlight the dynamic emitter/receiver roles of clean energy and oil markets, which shift depending on the time horizon. This indicates the critical importance of horizon-specific strategies for market participants and policymakers.

Madaleno et al. (2022) contribute to this line of inquiry by examining bidirectional causalities among green technology, green finance, environmental responsibility, and renewable energy using a time-varying causality approach over the 2014–2021 period. Their results confirm dynamic feedback loops among these variables, although the strength and direction of causality fluctuate over time, most notably declining during the COVID-19 shock. Interestingly, renewable energies are shown to consistently drive green finance rather than the reverse, suggesting that capital allocation follows rather than leads energy innovation demands.

Further bridging these market systems, Dai et al. (2023) and Ha et al. (2024) employ TVP-VAR and wavelet-based techniques to evaluate time-varying connectedness and volatility transmission among green assets, carbon allowances, and oil markets. These studies reveal complex asymmetric spillovers, especially during periods of heightened uncertainty. However, their focus is predominantly on asset-level volatility and sectoral indices, without disaggregating the origins of oil shocks or integrating regional dimensions of the green economy.

Taken together, the reviewed literature underscores a growing recognition of the multifaceted and time-sensitive interactions among green economy assets, carbon markets, and oil shocks. Existing research has made important strides in examining pairwise and, to a lesser extent, cross-market relationships. However, the prevailing approaches remain limited in the three following critical respects. First, a predominant reliance on static or symmetric modeling frameworks that overlook the evolving nature of market linkages. Second, an insufficient integration of regionally disaggregated green economies alongside carbon allowances and oil shocks. Third, a lack of attention to decomposed oil shocks, namely, disentangling them into demand-, supply-, and risk-driven innovations, each one related to a distinct source of systemic risk.

While prior studies have separately addressed carbon pricing dynamics, clean energy finance, and oil-induced spillovers, only few works have attempted to unify these dimensions under a single, asymmetric, time-varying analytical structure. Moreover, the limited application of advanced econometric techniques, such as TVP-VAR, to this integrated context has constrained the field's ability to model directional spillovers and crisis-sensitive connectedness patterns.

In this context, our study addresses the above-identified important gap by deploying a TVP-VAR framework to analyze the dynamic, asymmetric spillovers over the period 2010–2023 within a threefold system comprising regional green economies (Asia, Europe, and U.S.), EU Allowances (carbon credits), and disaggregated oil shocks. This approach not only accommodates the non-linearities and state dependencies inherent in these markets, but also captures the shifts in transmitter-receiver roles, particularly under major global disruptions such as the European debt crisis, COVID-19 pandemic, and the Russia-Ukraine conflict.

By offering a comprehensive view of the green-carbon-oil network through a regional and asymmetric lens, our research contributes to a more nuanced understanding of market interdependencies in the context of environmental finance. These insights hold direct relevance for policymakers, risk managers, and investors aiming to navigate the financial dimensions of the global low-carbon transition.

3. Data and econometric modelling framework

3.1. Data and summary statistics

We use the NASDAQ OMX Green Economy Index Family, which includes regional green energy stock indexes, to conduct the analysis. The performance of the regional green equity markets in the United States, Europe, and Asia are represented by the NASDAQ OMX Green Economy U.S. Index (GRNUSR), NASDAQ OMX Green Economy Europe Index (GRNEUR), and NASDAQ OMX Green Economy Asia Index (GRNASIAR), respectively. These indices cover businesses in all industries and offer a thorough understanding of how the green equity markets in these areas have performed. Additionally, we use ICE- European Union Allowance, or EU Allowance, as the carbon market variable. EU Allowance is expressed in EUR per ton of CO2 emissions. We break down the variations in WTI crude oil futures prices into three categories of shocks, which are supply, demand, and risk shocks (Ready, 2018; Umar, Gubareva, et al., 2021). The Chicago Board Options Exchange's volatility index, or VIX, is a good indicator of impending risk shocks. The percentage of returns on a worldwide stock index of companies that produce oil determines demand shocks. Supply shocks are the remaining part of the oil price volatility. The chosen sample period runs from November 29, 2010, to May 31, 2023. Data for this analysis is sourced from the NASDAQ and Datastream. The difference between the natural logarithm of two consecutive daily prices yields the continuously compounded return. Descriptive statistics results for oil shocks series, regional green economy indices, and EU Allowances are presented in Table 1. All indices, except the risk shock, exhibit a mean return close to zero. The green indices, along with EU Allowances, judging by their standard deviations, appear to be less risky. Among oil shocks, risk shocks display the highest volatility. The distributions of variables appear non-normal, evident from skewness, kurtosis, and the Jarque-Bera test.

To ensure the appropriateness of the TVP-VAR model, we conducted unit root tests on all series. The Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests were used to verify weak stationarity. Notably, the null hypothesis of the KPSS test is stationarity, distinguishing it from others. As reported in Table 1, the ADF and PP tests reject the null of a unit root, while the KPSS test confirms stationarity for all return series. This consistency across multiple test procedures strengthens the reliability of our inference. These findings justify the use of level data in the TVP-VAR framework. The optimal lag length was determined using the Bayesian Information Criterion (BIC) in a standard VAR setting and applied consistently to the time-varying model. This step ensures model parsimony and guards against overparameterization, which is especially important in time-varying frameworks. In addition, preliminary inspection of the return series revealed evidence of volatility clustering and structural breaks (see Figs. 1 and 2), supporting our choice of a time-sensitive modeling approach.

Table 2 displays unconditional correlations, revealing positive and significant correlations between regional green economies, carbon, and demand-based oil shocks, and negative and significant correlations with risk-based oil shocks. The correlation is very weak and non-significant in the case of supply-based shocks. A strong correlation is observed between regional economies and carbon, the strongest is between Europe and the USA (0.600), while oil shocks display no correlation.

Fig. 1 depicts the dynamics of green economies and EU Allowance prices, revealing similar patterns. These indices show a slight fluctuating trend, until the COVID-19 outbreak, which triggers a downward move in the markets, before exhibiting a significant upward trend after the pandemic. The EU Allowance price demonstrates a pattern of stable trend between 2010 and 2018, remaining below 20 Euros/ton, before experiencing an increasing trend from 2019, exceeding 100 in 2021. Its volatility has become more obvious since the pandemic in line with (Zheng, Yin, et al., 2021). The same is applicable for other indices whose prices increase from 600 to 1400 for Asia, 1000 to 2000 for Europe, and from 1500 to 5000 for the US between 2019 and 2021.

Fig. 2 shows a fat-tailed distribution and strong volatility clustering for all series. Oil output increased towards the end of 2019 as a result of OPEC's inability to reach a consensus on production restrictions and the heightened competition between Saudi Arabia and Russia for market dominance (Sikiru & Salisu, 2021). Risk shocks consistently display greater volatility, with more clusters in line with (Zheng, Yin, et al., 2021). The demand shock exhibits significant fluctuations, aligning with the COVID-19 impact. Due to this incident, China had a significant economic downturn, which had a negative effect on the world's need for oil (IEA's Oil Market Report, March 2020).

3.2. Econometric modeling framework TVP-VAR

We employ a methodology that combines approaches from Diebold and Yilmaz (2009, 2012) with the TVP-VAR (Time-Varying Parameters Vector Autoregression) framework developed by Koop and Korobilis (2014) to investigate the relationship among the

Table 1
Basic statistics.

	Mean	Stdev	Skewness	Kurtosis	J.B. test	ADF	PP	KPSS
Asia	0.000	0.011	−0.372	5.357	3851.1	−13.260***	−2936.7***	0.143
Europe	0.000	0.013	−0.773	9.290	11676.0	−14.289***	−2951.2***	0.034
US	0.000	0.014	−0.529	7.948	8464.0	−14.480***	−3456.5***	0.061
EUA	0.000	0.033	−0.935	14.268	27255.0	−15.798***	−3081.5***	0.396
Supply Shock (SS)	0.000	2.816	−3.003	113.329	1694801.0	−12.508***	−3128.6***	0.067
Demand Shock (DS)	0.000	1.235	−1.384	26.105	90689.0	−15.161***	−3340.1***	0.116
Risk shock (RS)	−0.009	7.534	1.011	5.540	4578.8	−15.162***	−2923.0***	0.628

Notes: The symbol ***, used in basic statistical analysis, indicates significance at the 0.01 level.

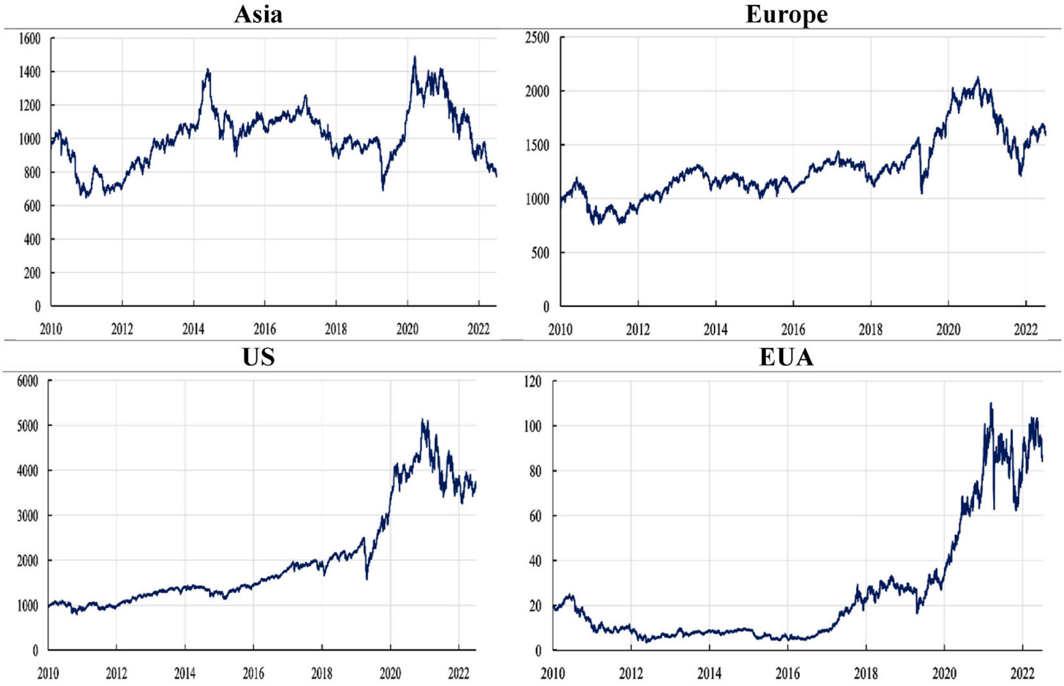


Fig. 1. Price dynamics.
Note: This figure shows the line graphs of the price series of green economy of Asia, Europe and US, and EU Allowance (EUA) as carbon market variable for the sample period from November 29, 2010 to May 31, 2023.

regional carbon economy, EU Allowances, and oil shocks. Baruník, Kočenda, and Vácha (2016) improved this strategy further, and Antonakakis, Chatziantoniou, and Gabauer (2020) improved it still further. We employ the TVP-VAR framework to calculate overall connectedness, paired connectedness, connectedness from each market to the framework, interconnectedness across every sector to the framework, and net connectedness. This method's primary benefit is that it uses a Kalman filter computation that takes decaying components into account, allowing variances to change with time. This method circumvents the drawbacks of employing a set rolling window size, which may result in values that are unduly irregular or smoothed and may cause the loss of important data. One way to formulate the TVP-VAR approach is as follows:

$$y_t = \beta_t z_{t-1} + \in_t;\ \in_t | F_{t-1} \sim N\,(0, S_t) \tag{1}$$

$$vec(\beta_t) = vec(\beta_{t-1}) + v_t; v_t | F_{t-1} \sim N\,(0, R_t) \tag{2}$$

where $\mathrm{y_t}$ **and** $\mathrm{z}_{\mathrm{t}} = \left[\mathrm{y_{t-1}}, \dots,\ \mathrm{y_t} - \mathrm{p}\right]'$ **represent** $\mathrm{N} \times 1$ **and** $\mathrm{P} \times 1$ **dimensional vectors, respectively.** $\mathrm{\beta_t}$ **is an** $\mathrm{N}\times\ \mathrm{N_p}$ **dimensional time-varying coefficient matrix and** ϵ_t **is an** $\mathrm{N} \times 1$ **dimensional error disturbance vector with an** $\mathrm{N} \times \mathrm{N}$ **time-varying variance-covariance matrix** $\mathrm{S_t}, \mathrm{vec}(\mathrm{\beta_t})$ **and** $\mathrm{v_t}$ **are** $\mathrm{N_p^2} \times 1$ **dimensional vectors and** $\mathrm{R_t}$ **is an** $\mathrm{N_p^2} \times \mathrm{N_p^2}$ **dimensional matrix. The vector moving average (VMA) model of the VAR (Vector Autoregression) system is used to compute the generalized impulse response functions (GIRF) and generalized forecast error variance decomposition (GFEVD), in accordance with the methodology described by Koop et al. (1996) and Pesaran and Shin (1998).**

$$y_t = \sum\nolimits_{j=0}^{\infty} L' W_t^j L \in_{t-j} \tag{3}$$

$$y_t = \sum\nolimits_{j=0}^{\infty} A_{it} \in_{t-j} \tag{4}$$

where $L = \left[\mathrm{I_{N,\dots}}\ \ \mathrm{0_P}\right]'$ **is** $\mathrm{N_p} \times \mathrm{N}$ dimensional matrix**,** $W = \left[\beta \mathrm{t};\ \mathrm{I_{N\ (p-1),}} \mathrm{0_{N\ (p-1) \times N}}\right]$ **is an** $\mathrm{N_p} \times \mathrm{N_p}$ dimensional matrix**, and** A_{it} **i s an** $\mathrm{N} \times \mathrm{N}$ dimensional matrix**. In a given variable i, the generalized impulse response functions (GIRFs) show how each variable responds to a shock. We compute the differences in a J-step-ahead forecast twice, once when variable i is shocked and once when it is not, because there is not a structural model available. This comparison sheds light on how the shock affected the relevant factors. This difference is measured by; it is ascribed to a shock in variable i.**

$$GIRF_t\left(K, \delta_{j,t} F_{t-1}\right) = E\left(y_{t+K} \middle| \in_{j,t} = \delta_{j,t} F_{t-1}\right) - E(Y_{t+K} | F_{t-1}) \tag{5}$$

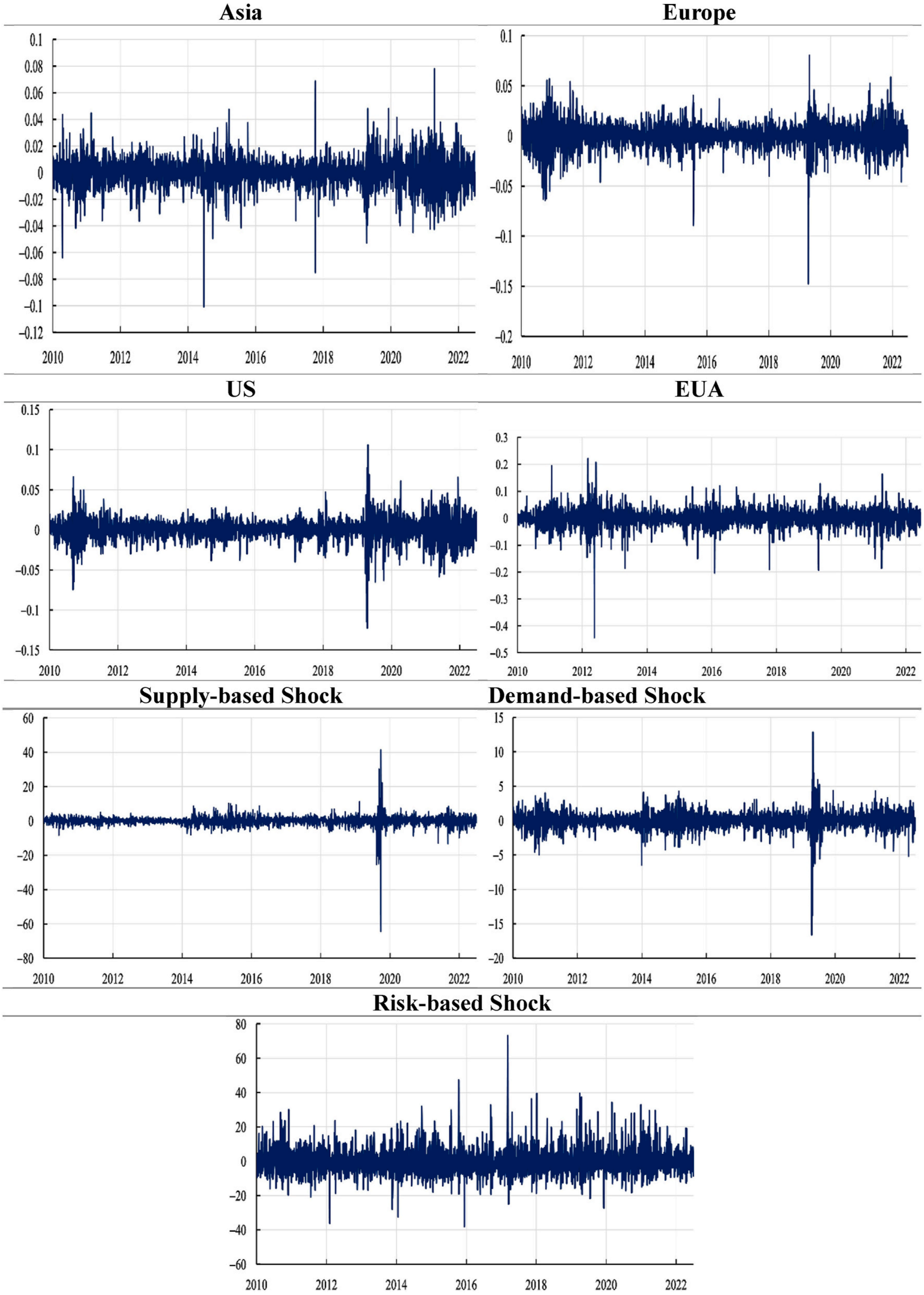


Fig. 2. Returns dynamics of green economy, EU Allowance (EUA) and oil shocks.

Note: This figure shows the return dynamics of green economies (Asia, Europe, US), EU Allowance (EUA), and the three types of oil shocks.

Table 2
Correlations.

	Asia	Europe	US	EUA	SS	DD	RS
Asia	1						
Europe	0.367***	1					
US	0.274***	0.600***	1				
EUA	0.081***	0.265***	0.165***	1			
SS	−0.008	0.014	0.010	−0.006	1		
DS	0.166***	0.543***	0.525***	0.222***	0	1	
RS	−0.430***	−0.423***	−0.197***	−0.102***	0	0	1

Notes: The symbol ***, used in correlation analysis, indicates significance at the 0.01 level.

$$\psi^{g}_{j,t}(K) = \frac{A_{K,t}S_t\in_{j,t}}{\sqrt{S_{jj,t}}}\ \frac{\delta_{j,t}}{\sqrt{S_{jj,t}}} \quad \delta_{j,t} = \sqrt{S_{jj,t}} \tag{6}$$

$$\psi^{g}_{j,t}(K) = \frac{A_{K,t}S_t\in_{j,t}}{\sqrt{S_{jj,t}}} \tag{7}$$

The expression $\psi^{g}_{j,t}$ describes the $GIRF_S$, which stands for the impulse response function of variable j over a forecast horizon K. $\delta_{j,t}$ is a selection vector that has a value 1 in the jth position and zero elsewhere. F_{t-1} represents the information available up to time $t-1$.

Next, we can calculate the GFEVD, which shows the proportion of variance in one variable compared to others, using the following method;

$$\tilde{\Phi}^{g}_{ij,t}(K) = \frac{\sum_{t=1}^{K-1}\Psi^{2,g}_{j,t}}{\sum_{j=1}^{N}\sum_{t=1}^{K-1}\Psi^{2,g}_{j,t}};\ \sum_{j=1}^{N}\tilde{\Phi}^{g}_{ij,t}(K) = 1 \text{ and } \sum_{j=1}^{N} N^{g}_{ij,t}(K) = N \tag{8}$$

Using equation (7), we can create a total connectivity index as follows in order to study how changes in one market index affect another market index that we are interested in studying.

$$C^{g}_{t}(K) = \frac{\sum_{i,j=1\ i\neq j}^{N}\tilde{\Phi}^{g}_{ij,t}(K)}{N}*100 \tag{9}$$

Studying the directional connectivity is quite fascinating. This approach considers three aspects of directional connectivity. First, it describes the total directed connectivity to other elements. At start, the total directed connectivity to others is written as;

$$C^{g}_{i\rightarrow j,t}(K) = \frac{\sum_{i,j=1\ i\neq j}^{N}\tilde{\Phi}^{g}_{ij,t}(K)}{\sum_{i,j=1}^{N}\tilde{\Phi}^{g}_{ij,t}(K)}*100 \tag{10}$$

Secondly, it considers the total directional connectedness from others, as follows;

$$C^{g}_{i\leftarrow j,t}(K) = \frac{\sum_{i,j=1\ i\neq j}^{N}\tilde{\Phi}^{g}_{ij,t}(K)}{\sum_{j=1}^{N}\tilde{\Phi}^{g}_{ij,t}(K)}*100 \tag{11}$$

The net total directional connectivity is calculated by subtracting equation (11) from equation (10) in the following manners;

$$C^{g}_{i,t}(K) = C^{g}_{i\rightarrow j,t}(K) - C^{g}_{i\leftarrow j,t}(K) \tag{12}$$

In equation (12), a positive value means that the network has a greater impact on index i's stock price than vice versa, whereas a negative value means that index i's stock process is driven by the network. We compute the net pairwise directional connectedness (NPDC) using the following formula in order to investigate bidirectional links further:

$$\mathrm{NPDC}_{i,j}(K) = \tilde{\Phi}^{g}_{ij,t}(K) - \tilde{\Phi}^{g}_{ji,t}(K) \tag{13}$$

As per equation (13), if *NPDC* is positive, it suggests that stock price in index *i* are primarily influenced by those in index *j*. Conversely, a negative *NPDC* indicates the opposite relationship, where stock price in index *i* influence those in index.

4. Empirical results

4.1. Static connectedness

The connectedness results for the full study period are shown in Table 3. The contributions of each series are represented by the diagonal elements, while the effects transmitted between series are represented by the off-diagonal elements. Columns show the contribution of each index to each other separately, while rows show each index's contribution to the "forecast error variance" of other indexes (Balcilar et al., 2021). Table 3 reveal that the United States (76.83 %) transmits the highest shock values, followed by Europe (69.88 %), while the lowest shocks are from the supply shocks (3.52 %), followed by global carbon (14.76 %) to other markets. When looking at oil shocks, the most significant spillover shocks occur from DS to the US (14.81 %), followed by DS to Europe (14.49 %).

When comparing the effects of various green economy stocks on carbon, Europe emerges as the primary contributor to global carbon with 6.47 %, followed by DS with 5.61 %. Carbon shocks transferred from the US and Asia are 1.44 % and 3.68 %, respectively. The results indicate a relationship between the green economy and environmental markets, consistent with (Tiwari et al., 2022), whose findings suggest connectedness between renewable energy markets and the environment (CO2).

With an emphasis on the mechanism of shock transmission from carbon to oil shocks and green economy stocks, carbon transmits 1.81 % shocks to Asia, 4.05 % shocks to Europe, 2.33 % of shocks to the US, and 4.25 % of shocks to DS. The higher shock transmission from green economy stocks to global carbon than from global carbon to green economy stocks indicates that the green economy market dominates the carbon markets. According to **(**Tiwari et al., 2022), this dominance is attributable to greater investment brought about by policy support, since environmental regulating rules also promote the development of renewable energy **(**Cao & Xie, 2023**).**

With a Total Connectedness Index (TCI) of 37.70 %, it can be inferred that 37.60 % of shocks originating from one variable tend to affect other variables. Significantly, carbon, the Asian green economy, supply, and risk are net recipients of shocks (4.77 %, 23.19 %, 1.54 %, and 27.58 %, respectively), whereas demand shocks, Europe, and the US are net transmitters of shocks (17.43, 30.2, and 9.45). These finding highlight how clean energy markets dominate the global carbon market and how demand shocks are the main mechanism for spreading spillovers. Furthermore, the main diagonal values show that within-index shocks account for 80.47 % of the global carbon index evolution, while 14.76 % is attributed to network connections, consistent with (Dogan et al., 2023). This aligns with the assertion by (Lyu & Scholtens, 2024) that internal forces account for the majority of the dynamics of carbon markets. The same finding is observed for SS and RS, where their dynamics are predominantly explained by internal factors. In contrast, most of the index movement in green economy indices, especially for US and Europe, is influenced by network connections when compared to global carbon.

Table 3

Static connectedness and spillover.

Overall	Asia	Europe	US	EUA	Supply Shock	Demand Shock	Risk Shock	FROM
Asia	55.77	12.01	14.98	1.81	0.59	7.6	7.24	44.23
Europe	5.46	47.54	18.77	4.05	0.51	14.49	9.18	52.46
US	4.67	18.91	53.37	2.33	0.5	14.81	5.4	46.63
EUA	1.44	6.47	3.68	80.47	0.69	5.61	1.65	19.53
Supply Shock	0.84	0.89	0.75	0.66	94.93	1.04	0.89	5.07
Demand Shock	2.7	16.75	15.94	4.25	0.57	57.88	1.92	42.12
Risk Shock	5.93	14.86	22.71	1.66	0.66	8.03	46.14	53.86
Contribution TO others	21.04	69.88	76.83	14.76	3.52	51.58	26.28	263.89
Including Own	76.81	117.43	130.2	95.23	98.46	109.45	72.42	TCI
NET directional connectedness	−23.19	17.43	30.2	−4.77	−1.54	9.45	−27.58	**37.70**
Positive	Asia	Europe	US	EUA	Supply Shock	Demand Shock	Risk Shock	FROM
Asia	66.23	10.69	12.32	2.07	0.76	5.74	2.2	33.77
Europe	5.25	56.9	17.87	3.26	0.95	12.95	2.81	43.1
US	3.75	17.32	59.71	2.43	1.23	14.16	1.4	40.29
EUA	1.38	4.68	3.79	84.26	0.99	3.91	0.98	15.74
Supply Shock	0.89	1.08	1.4	0.71	93.46	1.38	1.08	6.54
Demand Shock	1.84	13.18	14.23	2.82	1.5	63.77	2.67	36.23
Risk Shock	2.4	5.37	5.65	1.38	0.98	4.82	79.4	20.6
Contribution TO others	15.51	52.31	55.27	12.66	6.41	42.96	11.15	196.27
Including Own	81.74	109.21	114.98	96.92	99.88	106.73	90.54	TCI
NET directional connectedness	−18.26	9.21	14.98	−3.08	−0.12	6.73	−9.46	**28.04**
Negative	Asia	Europe	US	EUA	Supply Shock	Demand Shock	Risk Shock	FROM
Asia	60.89	11.11	15.45	1.6	0.69	7.86	2.41	39.11
Europe	5.13	53.31	18.57	4.28	0.62	15.72	2.37	46.69
US	4.88	17.08	58.18	2.28	0.74	15.67	1.18	41.82
EUA	1.67	6.3	3.56	81.48	0.91	5.07	1.01	18.52
Supply Shock	0.79	0.7	1.38	0.97	93.48	1.58	1.09	6.52
Demand Shock	2.9	15.91	15.34	3.59	1.14	59.77	1.35	40.23
Risk Shock	3.13	4.91	7.78	1.02	0.72	3.77	78.67	21.33
Contribution TO others	18.48	56.02	62.07	13.74	4.82	49.67	9.41	214.21
Including Own	79.37	109.32	120.25	95.23	98.3	109.45	88.08	TCI
NET directional connectedness	−20.63	9.32	20.25	−4.77	−1.7	9.45	−11.92	**30.60**

Notes: The table presents the results for connectedness/spillover for overall, positive and negative returns. The findings are derived from a TVP-VAR model with a Bayesian information criterion (BIC) and a 20-step-ahead GFEVD. The top section of table presents the overall connectedness, not accounting the asymmetry. The middle and lower sections display the spillover levels associated with positive and negative changes, respectively.

4.2. Dynamic total connectedness

The influence of economic events on the network under examination may not always be evident when looking solely at average connectedness results. To overcome this challenge, it is useful to use the TVP-VAR based connectivity technique. This approach allows for the analysis of dynamic connectedness within the global "Green-Carbon-Oil Shocks" system. By utilizing the TVP-VAR method, not only can we gain insights into the evolution of Total Connectedness Index (TCI) over time, but we can also elucidate how the roles of the variables within the network fluctuate with time. Furthermore, this approach serves as an alternative method to explore the effects of variables that undergo changes over time within the network, offering a more comprehensive understanding of the interconnectedness dynamics. The Total Connectedness Index (TCI) dynamic evolution is shown in Fig. 3 for the full sampling period, which runs from November 29, 2010, to May 31, 2023. TCI levels show significant fluctuations throughout this time, ranging from 40 % to 80 %. The peaks recorded during major international economic events, like the European Debt Crisis and the Oil Crisis, are especially noteworthy. The start of the COVID-19 pandemic coincides with another significant peak, which is followed by a subsequent fall until 2022, right before the start of the military conflict between Russia and Ukraine. The dramatic rise in TCI that occurred after the World Health Organization declared the COVID-19 pandemic on March 11, 2020, is a noteworthy development. This abrupt increase, which is more than 30 %, highlights the significant effects of this extraordinary.

These variations in TCI values confirm the index's responsiveness to large economic events, implying a greater degree of connectedness amid economic uncertainty. This is consistent with research by (Balcilar et al., 2021; Dogan, Madaleno, et al., 2022; Dogan, Majeed, et al., 2022; Tiwari et al., 2022) that found relationships to be stronger during times of crisis than they were during regular times, such as the oil crisis, Brexit referendum, and COVID-19 pandemic. According to Wei et al. (2023), market participants' over-interpretation and dissemination of information during crises is the cause of the increased interconnection. This finding is consistent with earlier study conducted during the COVID-19 pandemic (Bouri et al., 2021; Ding et al., 2022).

After then, TCI started to decline and eventually hit its lowest point of 30 %. Similarly, TCI saw a marginal increase of about 10 % following the onset of the military conflict between Russia and Ukraine. While the "Green-Carbon-Oil Shocks" system experienced some impact from the geopolitical exogenous event of the Russia-Ukraine military conflict, it was less pronounced than the impact of the COVID-19 pandemic. This finding echoes earlier research on financial market connectedness during the Russia-Ukraine conflict (Umar, Polat, et al., 2022).

We also calculated the dynamic total connectedness of positive and negative returns—represented by the green and red lines, respectively. The idea that return connectedness in the system reacts asymmetrically to positive and negative information shocks is further supported. It is clear that patterns are similar and that both positive and negative connections change with time. Moreover, the total connectedness of negative returns peaks before the total connectedness of positive returns after the exogenous shocks from COVID-19. This is consistent with past studies looking into the unequal relationship between carbon markets and other financial markets (Nie et al., 2021; Wen et al., 2020).

The dynamic evolution of the asymmetry connectedness indicator for both positive and negative returns is displayed in Fig. 4. The asymmetry indicator is obviously larger than zero, indicating that negative information in price returns has a higher effect on the global system. This outcome is in line with previous research by (Nie et al., 2021; Yang et al., 2023), which consistently demonstrated that because the negative spillover impact surpasses the positive spillover effect, the system is more sensitive to negative information. Furthermore, Fig. 4 shows a dramatic rise in the asymmetry connectedness indicator, which peaks after external shocks from the COVID-19 pandemic. This implies that the asymmetry in the spillover effect increases noticeably when the system is subjected to shocks from outside happenings. In the instance of the conflict between Russia and Ukraine, on the other hand, this observation is untrue because the positive spillover effect exceeds the negative one.

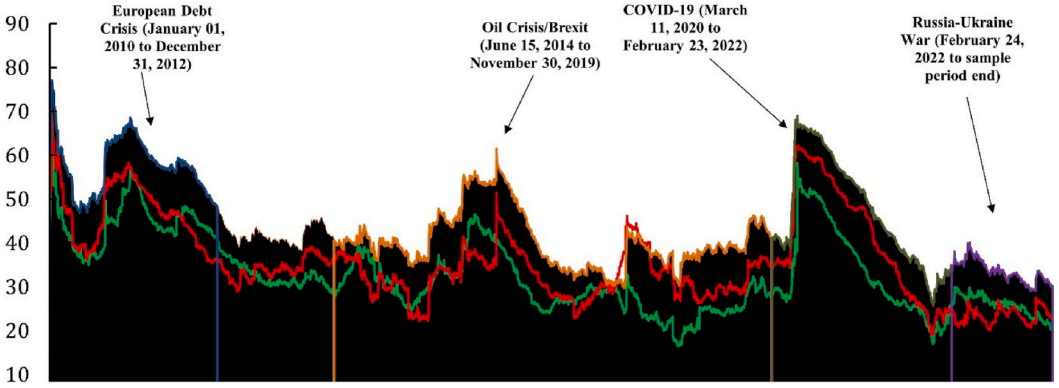


Fig. 3. Total spillover index considering asymmetric connectedness.
Notes. This figure shows the total spillover index based on asymmetric connectedness among green economy indices, carbon markets, and oil shocks from 2010 to 2023. The black shaded area represents the symmetric Total Connectedness Index (TCI), while the red and green lines indicate the time-varying connectedness attributable to negative and positive return shocks, respectively.

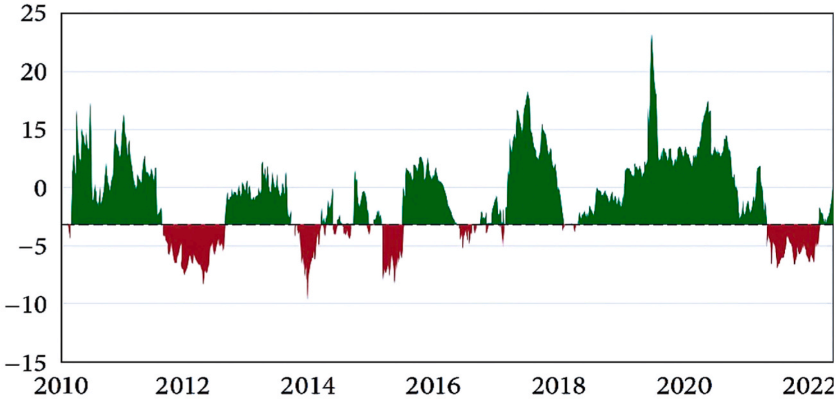


Fig. 4. Total spillover index considering asymmetric connectedness.
Note: This plot shows the net asymmetric spillover by subtracting negative from positive connectedness. Positive values indicate dominance of positive return spillovers, while negative values reflect periods where negative shocks drive the system. This net difference captures the directional bias in market sensitivity and helps assess whether optimism or pessimism dominates transmission dynamics at different times.

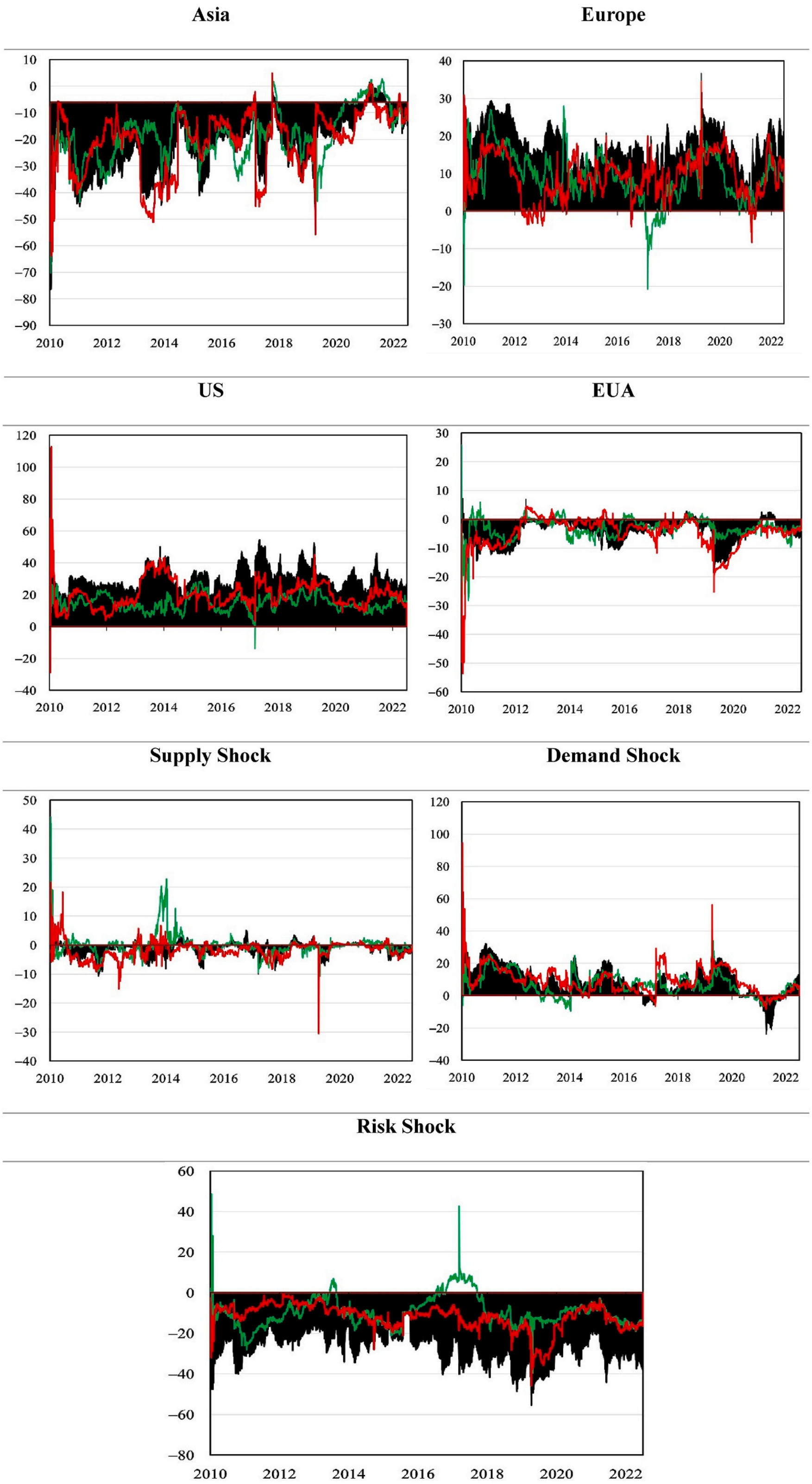
4.3. Net directional and net dynamic pairwise connectedness

For the period 2010 to 2022, Fig. 5 illustrates the dynamic net total directional connectedness of regional green equity markets, the EU Allowances (EUA), and oil-related shocks, namely demand- (DD), supply- (SS), and risk-driven (RS) shocks. The net connectedness index indicates either a variable acts as a net shock transmitter (positive values) or net receiver (negative values) of systemic innovations. The time-varying patterns reveal substantial heterogeneity across variables and over time, with changes in both direction and intensity of spillovers. The results confirm that the U.S. and European green equity markets are persistent net transmitters of systemic shocks, particularly during major crises such as the Eurozone debt crisis (2011–2013), the oil price collapse (2014–2016), and the COVID-19 pandemic (2020). The US exhibits a strong spike in net connectedness around 2010, likely reflecting the post-global financial crisis recovery and green investment initiatives. It maintains steady, positive spillover values thereafter, indicating a stable outward spillover role. The European index, while more volatile, also remains primarily positive throughout the period, underlining its leadership in green finance and policy influence. In contrast, the Asian green equity index consistently acts as a net receiver of systemic risk, especially during the first half of the sample. This reflects the region's lower integration into global green financial markets. However, from 2019 onward, Asia's net connectedness becomes less negative, suggesting a gradual convergence toward systemic neutrality, likely supported by its expanding role in renewable energy investment and climate policy development.

The EU Allowance (EUA), employed as a proxy for the carbon market, also behaves largely as a net receiver of shocks, consistent with its designation as a policy-driven and emergent commodity (Tan et al., 2020; Wang & Guo, 2018). For most of the sample, EU Allowance absorbs systemic risk rather than transmitting it. However, brief upward shifts in net connectedness occur during key regulatory episodes. Notably, in April 2016, the launch of EU Allowance forward contracts led to greater volatility in spot trading. This was followed by further reforms in late 2017, including the Market Stability Reserve and production restrictions. During these episodes, EU Allowance's net spillovers shifted upward, temporarily approaching or crossing zero, thus indicating a momentary transmitter role, especially under negative return conditions. Simultaneously, demand shocks (DD), which are typically strong transmitters, briefly showed signs of weakened or reversed spillovers, consistent with the findings of Zhao and Wen (2022) and Wu et al. (2022).

Among oil-related shocks, demand shocks (DD) are the most dominant and persistent net transmitters of systemic volatility. They consistently exhibit positive net connectedness, with pronounced spikes during global stress periods, especially the 2014–2016 oil price crash, 2018 trade tensions between China and US, and the COVID-19 outbreak. These results reinforce the interpretation of DD as a forward-looking driver of financial and energy market spillovers. Supply shocks (SS), in contrast, tend to hover near or below zero, acting primarily as net receivers. Short-lived positive spillovers appear in 2010, 2014, and 2016, but their role is typically passive. A sharp negative drop in SS is observed during the 2020 pandemic, reflecting the oil market's vulnerability to global supply chain disruption. Risk shocks (RS) demonstrate strong asymmetry across return regimes. They act as net receivers during market downturns in 2010–2014, 2016–2019, and 2020, but briefly emerge as transmitters under positive returns, especially in 2017, when investor sentiment and volatility repricing surge. This state-dependent behavior is consistent with the role of risk shocks as sentiment-sensitive volatility carriers.

The early 2020 period is particularly noteworthy. In addition to the COVID-19 shock, escalating U.S.-China trade tensions and new climate policy announcements led to a noticeable increase in net directional spillovers from both EU Allowances (EAU) and demand-driven shocks (DD). This suggests that carbon markets, while typically passive, can exert meaningful systemic influence during periods of environmental or geopolitical stress. This result is consistent with Wu et al. (2022). Moreover, the spillover structure changes under different market return regimes. During positive return phases, Europe and the US continue to dominate as net transmitters, while EU Allowance and Asia green equity market remain receivers. However, during negative returns, this structure partially reverses. EU Allowance occasionally becomes a marginal transmitter, whereas, depending on the context, risk-driven shocks (RS) show upward



(caption on next page)

Fig. 5. Net Directional Connectedness.

Notes: This figure presents the time-varying net spillover indices for each market and oil shock type. The black shaded area shows symmetric connectedness, while green and red lines depict spillovers due to positive and negative return asymmetries, respectively. Values above zero indicate net transmission of shocks; below zero indicates net absorption.

spikes, and the influence of demand-driven shocks (DD) moderates or reverses. These regime-dependent patterns emphasize the need to account for return asymmetry and policy context when analyzing spillovers.

In sum, Fig. 5 reveals that systemic risk transmission in green equity, carbon allowance, and oil-linked markets is highly dynamic, context-dependent, and asymmetrically distributed. Markets like Europe, the US, and demand-driven (DD) shocks consistently contribute to spillovers, while EU Allowances, Asia green equities, risk-driven (RS) and supply-driven (SS) shocks absorb systemic innovations, except during crisis episodes or regulatory transitions, when roles can temporarily reverse. These findings highlight the importance of incorporating shock type, return regime, and policy timing into spillover assessments. For investors and policymakers, understanding these patterns is critical for designing robust, state-contingent risk management frameworks that address the complex interdependencies shaping sustainable finance systems.

Fig. 6 explores the dynamic net pairwise directional connectedness, using black, green, and red lines to represent symmetric, positive, and negative spillover relationships, respectively. This analysis reveals critical asymmetries across regional markets and shock types, highlighting the evolving roles of green equity markets, carbon pricing instruments, and oil-related shocks. Asia consistently emerges as a net receiver of shocks from both Europe and the United States, with particularly negative spillovers observed during global volatility episodes such as the Eurozone debt crisis and the COVID-19 pandemic. While this receiver role persists throughout much of the sample, a gradual convergence toward neutrality is observed after 2019, possibly reflecting Asia's deeper integration into global clean energy markets. The relationship between Asia and EUA is relatively weak but still shows Asia as a modest net receiver, especially during regulatory episodes affecting carbon pricing. In contrast, the relationship between Europe and the United States is largely symmetric, marked by alternating spillovers without a clear directional dominance, indicative of mutual influence between two deeply integrated green finance systems. In turn, EU Allowance, representing the carbon market, predominantly acts as a net receiver from both Europe and the US, with short-lived but visible transitions into transmitter status during key policy reforms in late 2017 and the initial COVID-19 shock in early 2020. These brief spikes support findings that carbon markets, while generally passive, may exert limited systemic influence under exceptional regulatory or macro-financial conditions. Turning to oil shocks, demand shocks (DD) stand out as consistent transmitters of volatility, particularly toward Asia and EU Allowances, underscoring their central role in mediating energy-related macroeconomic spillovers. However, DD's transmitter role diminishes under negative return regimes, during which it occasionally absorbs shocks, especially during policy-driven disruptions in 2016–2017. Supply shocks (SS) are generally net receivers across all market pairs, absorbing shocks especially during the COVID-19 supply chain crisis, which generated a steep decline in SS-related net connectedness. Risk shocks (RS) exhibit asymmetric behavior: they act as net receivers during periods of market downturn, but shift into transmitter roles under positive returns, notably in 2017 and early 2020 when investor sentiment improved. Overall, the results confirm that systemic influence in green, carbon, and energy-linked markets is highly dynamic and dependent on region, return regime, and event context. Green equity indices in Europe and the US remain key transmitters, whereas Asia green equities and EU Allowances typically serve as receivers of market stress. Among oil shocks, demand shocks dominate spillover transmission, while supply and risk shocks demonstrate more conditional behavior. These findings reinforce the need for adaptive, state-contingent risk management frameworks and stress the relevance of macro-financial events and environmental policy transitions in shaping interconnectedness.

5. Discussion

This study provides a comprehensive analysis of the dynamic, asymmetric interrelationships between regional green economies, carbon markets, and disaggregated oil shocks, utilizing a TVP-VAR model. The findings contribute to the growing body of literature on environmental finance by elucidating the complex and evolving transmission mechanisms underlying these interlinked markets. This section interprets the results within theoretical and empirical frameworks and draws practical implications for investors and policymakers.

While the TVP-VAR framework has been previously employed in financial economics, our study presents a notable methodological advancement by integrating, within a single analytical structure, the three distinct domains: namely, regional green equity markets, carbon allowances, and decomposed demand-, supply-, and risk-driven oil shocks. This multimarket-market approach, resorting to disentangling oil price innovations contrasts with earlier studies that tend to focus on bilateral relationships or rely on symmetric models. By explicitly considering the intensity and the direction of spillovers, we offer a richer understanding of systemic risk propagation in climate-sensitive financial systems.

Our results indicate that the demand-driven oil shocks are the most potent transmitters of systemic spillovers in the green-carbon-oil system. This can be causally attributed to their role as proxies for global macroeconomic activity. An increase in oil demand generally signals economic expansion, which in turn amplifies industrial output and emissions. These developments elevate the demand for carbon allowances under cap-and-trade schemes, particularly within the EU ETS, and simultaneously stimulate investment in green sectors as part of long-term decarbonization strategies. As such, demand shocks propagate through multiple channels, including macroeconomic, regulatory, and investment-related ones, thereby intensifying their innovation transmission impact. These multi-channel dynamics result in demand-driven shocks exerting sustained spillovers toward green equities and carbon markets, Asia

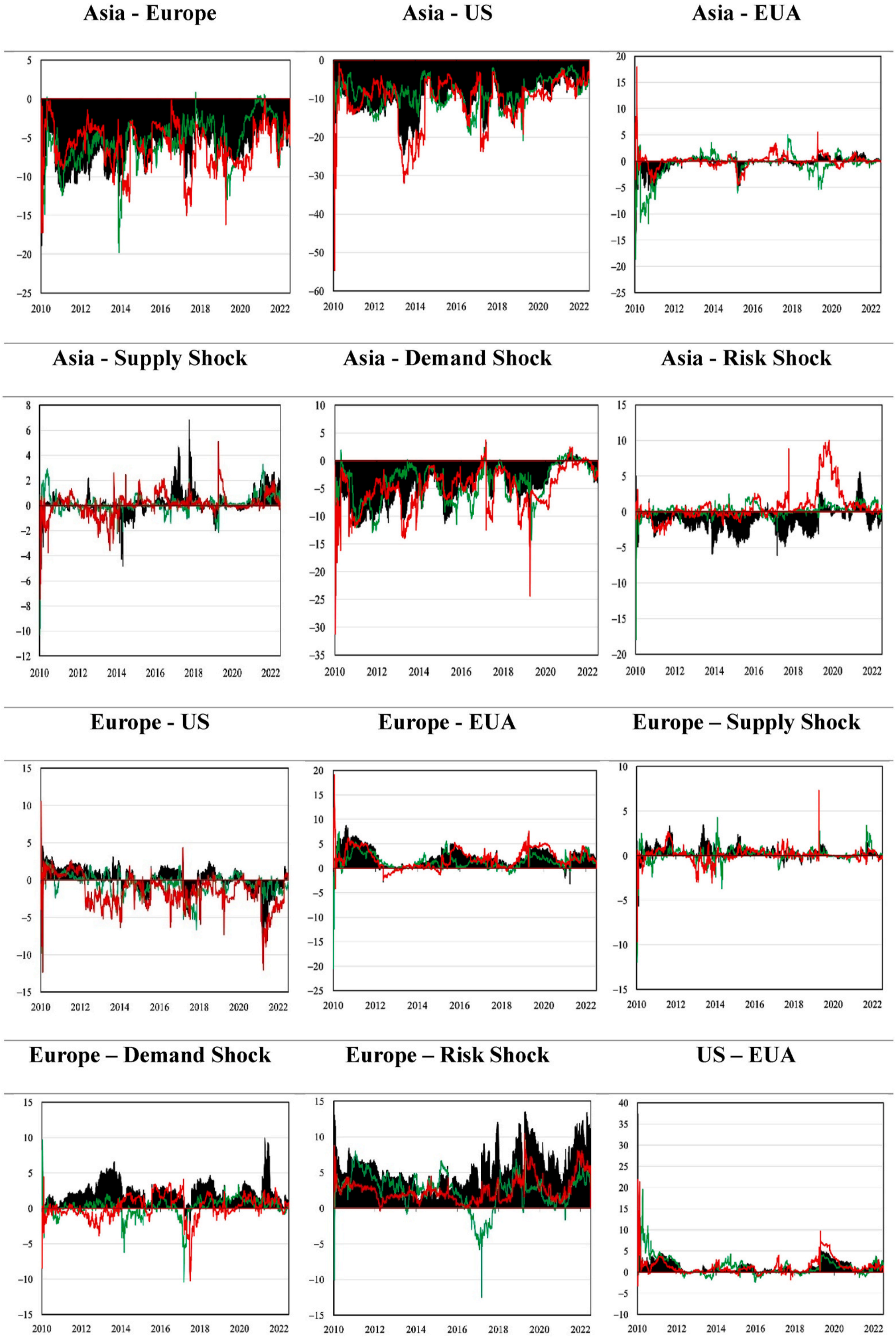


Fig. 6. Net Directional Pairwise Connectedness.

Notes: This figure displays the net pairwise directional spillover indices across various pairs within the green-carbon-oil system. Each panel illustrates the net transmission from one source to a recipient. The black area represents symmetric connectedness, whereas the green and red lines depict the components attributed to positive and negative return spillovers, respectively. Values above zero indicate that the originating market or shock acts as a net transmitter, while values below zero indicate a net receiver role.

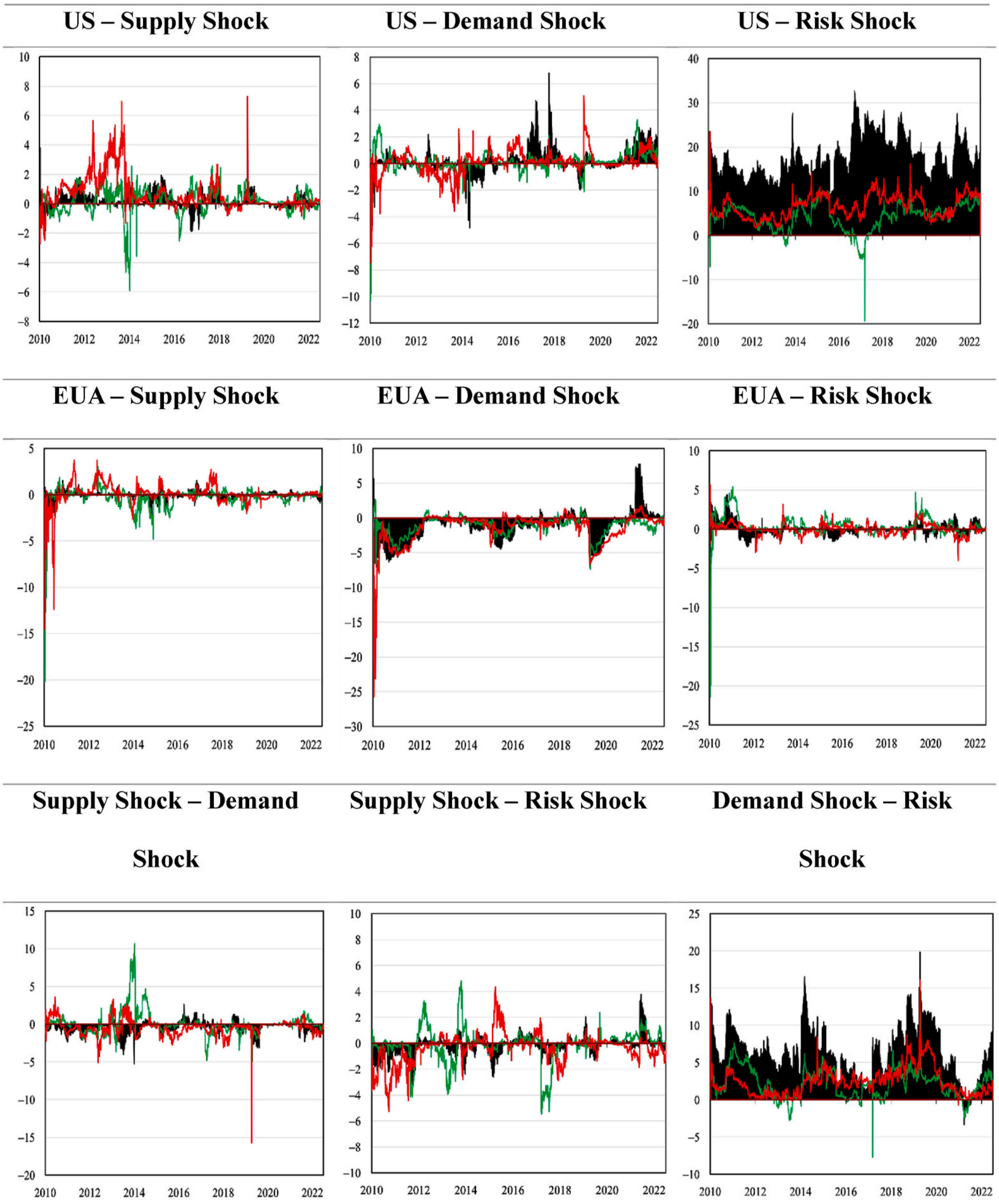

US – Supply Shock
US – Demand Shock
US – Risk Shock
EUA – Supply Shock
EUA – Demand Shock
EUA – Risk Shock
Supply Shock – Demand Shock
Supply Shock – Risk Shock
Demand Shock – Risk Shock

Fig. 6. (*continued*).

green economy and EU Allowances. However, under negative return regimes – particularly in 2016–2017 – this transmitter role weakens and the demand-driven oil shocks occasionally absorb systemic innovations. This reversed transmitter/receiver role reflects the impact of policy-related uncertainty on energy demand and investment expectations. In contrast, the supply-driven oil shocks consistently appear as net receivers across all pairwise links. They often are exogenous in nature, being induced by geopolitical tensions, production caps, or logistical disruptions. As such, they introduce uncertainty into global supply chains and energy commodity prices, which in turn distort carbon allowance valuations due to their sensitivity to energy costs. Although the immediate macroeconomic effects of the supply-driven oil shocks are limited, their influence manifests through heightened volatility and speculative repositioning in related asset classes. In turn, the risk-driven oil shocks reflect market sentiment and investor risk aversion. The CBOE Oil Volatility Index (OVX) usually captures the risk-driven oil shocks. These shocks exert asymmetric effects, influencing a range of asset classes, comprising green financial instruments, which may be particularly sensitive to investor risk aversion due to relatively recent expansion of green finance and insufficient liquidity in green asset markets. Elevated risk aversion tends to suppress capital inflows into green assets, leading to transient disinvestment and risk contagion. This mechanism underscores the vulnerability of green finance to broader market sentiment, even when fundamental sustainability indicators remain unchanged. The directional connectedness results underscore the region-specific transmission roles of green economies. The European and Unites States green equity indices consistently act as net shock transmitters, likely due to their deeper financial markets, more mature ESG investment frameworks, and institutional investor participation. These markets often respond proactively to global developments, setting the tone for sustainability-related capital flows. The Asian green index, in contrast, functions more as a shock absorber, potentially due to regulatory asymmetries, lower liquidity, and relatively later adoption of green finance principles. Although this receiver role persists through most of the sample, a gradual convergence toward systemic neutrality is observed after 2019, likely due to Asia's growing integration into global clean energy markets. The carbon allowance market, particularly the EU ETS, is also found to be a net recipient of shocks. This finding points to the susceptibility of the carbon allowance market to exogenous pressures rather than autonomous shock generation. This reflects the policy-driven nature of carbon markets, whose pricing mechanisms are often more reactive than proactive, depending on emissions cap adjustments and compliance requirements.

In terms of time dynamics, connectedness peaks align with major global crises. The European debt crisis, the COVID-19 pandemic, and the Russia-Ukraine conflict each coincides with surges in the Total Connectedness Index (TCI), suggesting that economic or geopolitical stress amplifies cross-market linkages. This behavior is consistent with the contagion theory, which posits that correlation structures change and intensify during the periods of market distress. Hence, this serves as an indication that currently the environmental finance is not immune to the broader systemic pressures, despite its normative association with long-term investment horizons.

The study contributes to the theory by empirically validating the endogenous role of oil market dynamics in influencing both carbon pricing and green investment behavior. It extends the resource dependence theory by showing that markets reliant on fossil fuel dynamics also condition the evolution of sustainability-linked assets. Moreover, the TVP-VAR methodology uncovers state-dependent variations in spillover intensity and direction, aligning with the tenets of regime-dependence and market-state contingency models in financial econometrics. Empirically, this research expands upon prior studies such as Zheng, Yin, et al. (2021), Ren et al. (2022), and Dai et al. (2023), by integrating a three-pillar system (green-carbon-oil) and disaggregating oil shocks into specific causal categories, namely demand-, supply-, and risk driven innovations. Whereas prior studies often employed static models or focused on pairwise relationships, our approach offers a temporally granular, regionally disaggregated, and causally rich portrayal of market interdependence.

The identification of dominant transmitters and receivers of shocks has significant practical implications. For investors, understanding that the US and European green indices act as early warning systems can support the design of preemptive portfolio adjustments. Green assets, often perceived as defensive or long-term, may also serve as systemic barometers during periods of elevated uncertainty. For policymakers, the consistent absorption of shocks by the carbon market underscores the importance of regulatory stabilization tools. Market-based instruments such as price floors, liquidity buffers, or flexible compliance mechanisms could help insulate carbon allowances from excessive external volatility. Notably, EU Allowance's brief transmitter episodes, especially under negative return conditions during regulatory shocks in 2017 and COVID-driven volatility in 2020 highlight the need for robust policy signaling to avoid market overreaction. Additionally, insights into the asymmetric response of markets to negative news emphasize the need for transparent and consistent policy signaling to mitigate investor overreaction. Finally, the systemic nature of oil demand-driven shocks suggests that macroprudential policies and energy transition frameworks must account for their ripple effects across sustainability-linked asset classes. Furthermore, risk managers should incorporate directional and time spillover metrics into stress-testing and scenario analysis frameworks to better anticipate contagion pathways in volatile market environments.

6. Conclusion

This study investigates the dynamic asymmetric spillovers within the three-pillar green-carbon-oil system by analyzing the time-varying connectedness among regional green economies (Asia, Europe, and US), the European Union carbon allowance market, and the three disaggregated demand-, supply-, and risk-driven oil shocks over the period from November 2010 to May 2023. Using the TVP-VAR methodology, we uncover the evolving structure of systemic interactions and directional dependencies across these markets.

Our findings provide innovative insights, relevant in several aspects. First, this is the pioneering study to integrate regional green economies with the disentangled demand-, supply-, and risk-driven oil shocks in a unified dynamic spillover framework. This multimarket-market perspective goes beyond the bilateral or static models prevalent in the literature and allows us to detect both directional and asymmetric transmission mechanisms. Second, our approach captures the distinct roles of regional green equity markets, showing that Europe and the US act as consistent net transmitters of shocks, whereas Asia green economy and EU Allowance market are primarily net recipients. These novel insights are unattainable in studies focusing on aggregated or single-region data. However, the above-reported predominant transmitter-receiver roles are not static, but time-varying. For instance, Asia green economy shows convergence toward a more neutral stance post-2019, whereas EU Allowance temporarily acts as a transmitter under negative return conditions during major policy changes in 2017 and throughout crisis periods. Third, by aligning spillover dynamics with major economic disruptions, such as COVID-19 and the European Debt Crisis, we demonstrate that environmental and energy-related financial markets exhibit crisis-contingent integration patterns, expanding the scope of systemic risk analysis.

Additionally, our disaggregation of oil shocks reveals heterogeneous causal pathways. The demand-driven shocks, reflecting macroeconomic expansion, exert broad systemic influence, whereas the supply shocks induce volatility mostly through the cost channels. In turn, the risk-driven shocks affect green markets via sentiment-driven reallocations. It is worth noting that the demand-driven shocks emerge as dominant spillover transmitters, particularly toward Asia green economy and EU carbon allowance market, though their influence weakens under negative return regimes. In contrast, the supply- and risk-driven shocks act primarily as net receivers, but may temporarily transmit volatility under specific market conditions, such as in 2017 or in early 2020. These distinctions contribute to a more granular understanding of the mechanics linking traditional and sustainable financial systems.

The results carry direct implications for financial decision-making and environmental policy. For investors and risk managers, identifying which markets serve as early transmitters or delayed absorbers of shocks, our findings supports the design of more responsive portfolio strategies. For policymakers, understanding that carbon markets absorb rather than propagate shocks, our outcomes emphasize the importance of regulatory cushioning mechanisms during periods of heightened uncertainty. However, our findings also reveal that under certain regimes, particularly during crisis or reform episodes, carbon markets can briefly transition into transmitter roles, suggesting the need for adaptive regulatory frameworks.

Still, our research present certain opportunities for further improvement. Herewith we acknowledge that while the TVP-VAR framework effectively captures dynamic interdependencies, it does not account for structural breaks that may result from sudden regulatory shifts or innovation shocks. Furthermore, reliance on daily data may obscure intraday volatility patterns. Future research could address these limitations by incorporating higher-frequency data, regime-switching models, and sector-specific green instruments to further refine causal insights. Furthermore, examining the effects of policy announcements, reforms in carbon pricing mechanisms, or major technological shifts could enrich our understanding of causal transmission channels. The above-mentioned research directions indicate several avenues for future research.

In sum, the three-pillar green-carbon-oil system is characterized by multifaceted and dynamic interrelationships shaped by both market fundamentals and exogenous shocks. The systemic importance of demand-driven shocks, the persistent transmitter roles of Europe and the US, the conditional behavior of supply- and risk-driven shocks, and the reactive posture of Asia green economy and EU carbon allowance market collectively emphasize the need for context-aware risk strategies. Continued empirical scrutiny and methodological refinement are essential for enhancing resilience in climate-conscious financial systems.

CRediT authorship contribution statement

Waqas Hanif: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Project administration, Writing – original draft, Writing – review & editing, Visualization. **Rim El Khoury:** Conceptualization, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Validation, Visualization. **Mariya Gubareva:** Conceptualization, Investigation, Formal analysis, Data curation, Resources, Writing – original draft, Writing – review & editing, Validation, Project administration, Visualization. **Tamara Teplova:** Conceptualization, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Validation, Visualization.

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Data availability

Data will be made available on request.

References

Ali, S., Naveed, M., Gubareva, M., & Vo, X. V. (2024). Reputational contagion from the silicon valley bank debacle. *Research in International Business and Finance, 69*, Article 102275. https://doi.org/10.1016/j.ribaf.2024.102275

Ali, S., Umar, M., Gubareva, M., & Vo, X. V. (2024). Extreme connectedness between NFTs and US equity market: A sectoral analysis? *International Review of Economics & Finance, 91*, 299–315. https://doi.org/10.1016/j.iref.2024.01.037

Ashfaq, S., Liangrong, S., Waqas, F., Gulzar, S., Mujtaba, G., & Nasir, R. M. (2024). Renewable energy and green economic growth nexus: Insights from simulated dynamic ARDL. *Gondwana Research, 127*, 288–300. https://doi.org/10.1016/j.gr.2023.08.014

Aziz, M., Umar, Z., Gubareva, M., Sokolova, T., & Vo, X. V. (2022). ASEAN-5 forex rates and crude oil: Markov regime-switching analysis. *Applied Economics, 54*(54), 6234–6253. https://doi.org/10.1080/00036846.2022.2083066

Balcilar, M., Gabauer, D., & Umar, Z. (2021). Crude oil futures contracts and commodity markets: New evidence from a TVP-VAR extended joint connectedness approach. *Resources Policy, 73*. https://doi.org/10.1016/j.resourpol.2021.102219

Bloom, N. (2009). The impact of uncertainty shocks. *Econometrica, 77*(3), 623–685. https://www.jstor.org/stable/40263840.

Bossman, A., Gubareva, M., & Teplova, T. (2023a). EU sectoral stocks amid geopolitical risk, market sentiment, and crude oil implied volatility: An asymmetric analysis of the Russia-Ukraine tensions. *Resources Policy, 82*, Article 103515. https://doi.org/10.1016/j.resourpol.2023.103515

Bossman, A., Gubareva, M., & Teplova, T. (2023b). Economic policy uncertainty, geopolitical risk, market sentiment, and regional stocks: Asymmetric analyses of the EU sectors. *Eurasian Economic Review, 13*, 321–372. https://doi.org/10.1007/s40822-023-00234-y

Bouri, E., Cepni, O., Gabauer, D., & Gupta, R. (2021). Return connectedness across asset classes around the COVID-19 outbreak. *International Review of Financial Analysis, 73*. https://doi.org/10.1016/j.irfa.2020.101646

Cao, G., & Xie, F. (2023). Extreme risk spillovers across energy and carbon markets: Evidence from the quantile extended joint connectedness approach. *International Journal of Finance & Economics*. https://doi.org/10.1002/ijfe.2781

Çelik, I., Sak, A. F., Höl, A.Ö., & Vergili, G. (2022). The dynamic connectedness and hedging opportunities of implied and realized volatility: Evidence from clean energy ETFs. *The North American Journal of Economics and Finance, 60*, Article 101670. https://doi.org/10.1016/j.najef.2022.101670

Chatziantoniou, I., Abakah, E. J. A., Gabauer, D., & Tiwari, A. K. (2022). Quantile time–frequency price connectedness between green bond, green equity, sustainable investments and clean energy markets. *Journal of Cleaner Production, 361*, Article 132088. https://doi.org/10.1016/j.jclepro.2022.132088

Dai, Z., Zhang, X., & Yin, Z. (2023). Extreme time-varying spillovers between high carbon emission stocks, green bond and crude oil: Evidence from a quantile-based analysis. *Energy Economics, 118*, Article 106511. https://doi.org/10.1016/j.eneco.2023.106511

Dechezleprêtre, A., Nachtigall, D., & Venmans, F. (2023). The joint impact of the european union emissions trading system on carbon emissions and economic performance. *Journal of Environmental Economics and Management, 118*, Article 102758. https://doi.org/10.1016/j.jeem.2022.102758

Ding, Q., Huang, J., & Zhang, H. (2022). Time-frequency spillovers among carbon, fossil energy and clean energy markets: The effects of attention to climate change. *International Review of Financial Analysis, 83*. https://doi.org/10.1016/j.irfa.2022.102222

Dogan, E., Luni, T., Majeed, M. T., & Tzeremes, P. (2023). The nexus between global carbon and renewable energy sources: A step towards sustainability. *Journal of Cleaner Production, 416*. https://doi.org/10.1016/j.jclepro.2023.137927

Dogan, E., Madaleno, M., Taskin, D., & Tzeremes, P. (2022a). Investigating the spillovers and connectedness between green finance and renewable energy sources. *Renewable Energy, 197*, 709–722.

Dogan, E., Majeed, M. T., & Luni, T. (2022b). Analyzing the nexus of COVID-19 and natural resources and commodities: Evidence from time-varying causality. *Resources Policy, 77*. https://doi.org/10.1016/j.resourpol.2022.102694

Esparcia, C., & Gubareva, M. (2024). ESG rating changes and portfolio returns: A wavelet analysis across market caps. *Finance Research Letters, 63*, Article 105306. https://doi.org/10.1016/j.frl.2024.105306

Ghosh, B., Gubareva, M., Zulfiqar, N., & Bossman, A. (2024). Is there a nexus between NFT, DeFi, and carbon allowances during extreme events? *China Finance Review International, 14*(3), 456–479. https://doi.org/10.1108/CFRI-03-2023-0057

Ghosh, B., Pham, L., Gubareva, M., & Teplova, T. (2023b). Energy transition metals and global sentiment: Evidence from extreme quantiles. *Resources Policy, 86-A*, Article 104170. https://doi.org/10.1016/j.resourpol.2023.104170

Gubareva, M. (2021). The impact of Covid-19 on liquidity of emerging market bonds. *Finance Research Letters, 41*, Article 101826. https://doi.org/10.1016/j.frl.2020.101826

Gubareva, M., Bossman, A., & Teplova, T. (2023b). Stablecoins as the cornerstone in the linkage between the digital and conventional financial market. *The North American Journal of Economics and Finance, 68*, Article 101979. https://doi.org/10.1016/j.najef.2023.101979

Gubareva, M., & Gomes, O. (2019). On the edge of climate change: In a search of an adequate agent-based methodology to model environmental dynamics. In T. Sequeira, & L. Reis (Eds.), *Climate change and global development. Contributions to economics*. Cham: Springer. https://doi.org/10.1007/978-3-030-02662-2_3.

Gubareva, M., Shafiullah, M., & Teplova, T. (2025). Cross-quantile risk assessment: The interplay of crude oil, artificial intelligence, clean tech, and other markets. *Energy Economics, 141*, Article 108085. https://doi.org/10.1016/j.eneco.2024.108085

Gubareva, M., Umar, Z., Sokolova, T., & Antonyuk, V. (2023a). For whom does it pay to be a moral capitalist? Sustainability of corporate financial performance of ESG investment. *PLoS One, 18*(5), Article e0285027. https://doi.org/10.1371/journal.pone.0285027

Gubareva, M., Umar, Z., Sokolova, T., & Vo, X. V. (2022). Astonishing insights: Emerging market debt spreads throughout the pandemic. *Applied Economics, 54*(18), 2067–2076. https://doi.org/10.1080/00036846.2021.1984383

Gubareva, M., Umar, Z., Teplova, T., & Tran, D. K. (2023d). Decoupling between the energy and semiconductor sectors during the pandemic: New evidence from wavelet analysis. *Emerging Markets Finance and Trade, 59*(6), 1707–1719. https://doi.org/10.1080/1540496X.2022.2149258

Gubareva, M., Umar, Z., Teplova, T., & Vo, X. V. (2023c). Flights-to-quality from EM bonds to safe-haven US treasury securities: A time-frequency analysis. *Emerging Markets Finance and Trade, 59*(2), 338–362. https://doi.org/10.1080/1540496X.2022.2103399

Ha, L. T. (2023). Dynamic connectedness between green energy and carbon risk during Russia-Ukraine conflict: New evidence from a wavelet analysis. *Environmental Science and Pollution Research, 30*, 79297–79314. https://doi.org/10.1007/s11356-023-27954-7

Ha, L. T., Bouteska, A., Sharif, T., & Abedin, M. Z. (2024). Dynamic interlinkages between carbon risk and volatility of green and renewable energy: A TVP-VAR analysis. *Research in International Business and Finance, 69*, Article 102278. https://doi.org/10.1016/j.ribaf.2024.102278

Hanif, W., Khoury, R., & Gubareva, M. (2025). How do GCC countries stocks interact with US and European debt markets? *International Journal of Finance & Economics*. https://doi.org/10.1002/ijfe.3129

Hanif, W., Teplova, T., Rodina, V., Alomari, M., & Mensi, W. (2023). Volatility spillovers and frequency dependence between oil price shocks and green stock markets. *Resources Policy, 85-B*, Article 103860. https://doi.org/10.1016/j.resourpol.2023.103860

He, F., Feng, Y., & Hao, J. (2022). Information disclosure source, investors' searching and stock price crash risk. *Economics Letters, 210*, Article 110202. https://doi.org/10.1016/j.econlet.2021.110202

Houssam, N., Ibrahiem, D. M., Sucharita, S., El-Aasar, K. M., Esily, R. R., & Sethi, N. (2023). Assessing the role of green economy on sustainable development in developing countries. *Heliyon, 9*(6), Article e17306. https://doi.org/10.1016/j.heliyon.2023.e17306

Huang, S., Bossman, A., Gubareva, M., & Teplova, T. (2024). International transmission of shocks and African forex markets. *Energy Economics, 131*, Article 107382. https://doi.org/10.1016/j.eneco.2024.107382

Jahanger, A., Ali, M., Balsalobre-Lorente, D., Samour, A., Joof, F., & Tursoy, T. (2023). Testing the impact of renewable energy and oil price on carbon emission intensity in China's transportation sector. *Environmental Science and Pollution Research, 30*, 82372–82386. https://doi.org/10.1007/s11356-023-28053-3

Ji, Q., & Zhang, D. (2019). China's crude oil futures: Introduction and some stylized facts. *Finance Research Letters, 28*, 376–380. https://doi.org/10.1016/j.frl.2018.06.005

Kocaarslan, B., & Soytas, U. (2021). Reserve currency and the volatility of clean energy stocks: The role of uncertainty. *Energy Economics, 104*, Article 105645. https://doi.org/10.1016/j.eneco.2021.105645

Li, B., & Haneklaus, N. (2022). Reducing CO2 emissions in G7 countries: The role of clean energy consumption, trade openness and urbanization. *Energy Reports, 8* (S4), 704–713. https://doi.org/10.1016/j.egyr.2022.01.238

Liang, Z., & Qamruzzaman, M. (2022). An asymmetric investigation of the nexus between economic policy uncertainty, knowledge spillover, climate change, and green economy: Evidence from BRIC nations. *Frontiers in Environmental Science, 9*, Article 807424. https://www.frontiersin.org/articles/10.3389/fenvs.2021.807424/full.

Lynch, B., & O'Hagan-Luff, M. (2024). Finally, it seems to be working – The evolving valuation effect of the european Union's emissions trading system. *The European Journal of Finance, 30*(3), 229–248. https://doi.org/10.1080/1351847X.2023.2204195

Lyu, C., & Scholtens, B. (2024). Integration of the international carbon market: A time-varying analysis. *Renewable and Sustainable Energy Reviews, 191*. https://doi.org/10.1016/j.rser.2023.114102

Madaleno, M., Dogan, E., & Taskin, D. (2022). A step forward on sustainability: The nexus of environmental responsibility, green technology, clean energy and green finance. *Energy Economics, 109*, Article 105945. https://doi.org/10.1016/j.eneco.2022.105945

Mensi, W., Gubareva, M., Ko, H.-U., Vo, X., & Kang, S. (2023). Tail spillover effects between cryptocurrencies and uncertainty in The Gold, oil, and stock markets. *Financial Innovation, 9*, 92. https://doi.org/10.1186/s40854-023-00498-y

Mensi, W., Gubareva, M., & Teplova, T. (2025). Risk transmission between oil price shocks and major equity indices across bull and bear markets over various time Horizons. *The North American Journal of Economics and Finance, 79*, Article 102459. https://doi.org/10.1016/j.najef.2025.102459

Mishra, M., Desul, S., Santos, C.A.G. et al. A bibliometric analysis of sustainable development goals (SDGs): A review of progress, challenges, and opportunities. Environment, Development and Sustainability. https://doi.org/10.1007/s10668-023-03225-w.

Naveed, M., Ali, S., Gubareva, M., & Omri, A. (2024). When giants fall: Tracing the ripple effects of silicon valley bank (SVB) collapse on global financial markets. *Research in International Business and Finance, 67-A*, Article 102160. https://doi.org/10.1016/j.ribaf.2023.102160

Nie, D., Li, Y., & Li, X. (2021). Dynamic spillovers and asymmetric spillover effect between the carbon emission trading market, fossil energy market, and new energy stock market in China. *Energies, 14*(19). https://doi.org/10.3390/en14196438

Patel, R., Gubareva, M., Chishti, M., & Teplova, T. (2024). Connectedness between healthcare cryptocurrencies and major asset classes: Implications for hedging and investments strategies. *International Review of Financial Analysis, 93*, Article 103181. https://doi.org/10.1016/j.irfa.2024.103181

Ready, R. C. (2018). Oil prices and the stock market. *Review of Finance, 22*(1), 155–176.

Reboredo, J. C., Ugolini, A., & Ojea-Ferreiro, J. (2022). Do green bonds de-risk investment in low-carbon stocks? *Economic Modelling, 108*, Article 105765. https://doi.org/10.1016/j.econmod.2022.105765

Ren, X., Li, Y., Qi, Y., & Duan, K. (2022). Asymmetric effects of decomposed oil-price shocks on the EU carbon market dynamics. *Energy, 254-B*, Article 124172. https://doi.org/10.1016/j.energy.2022.124172

Sikiru, A. A., & Salisu, A. A. (2021). Hedging with financial innovations in the Asia-Pacific markets during the COVID-19 pandemic: The role of precious metals. *Quantative Finance Economics, 5*(2), 352–372.

Tan, X., Sirichand, K., Vivian, A., & Wang, X. (2020). How connected is the carbon market to energy and financial markets? A systematic analysis of spillovers and dynamics. *Energy Economics, 90*. https://doi.org/10.1016/j.eneco.2020.104870

Tiwari, A. K., Abakah, E. J. A., Gabauer, D., & Dwumfour, R. A. (2022). Dynamic spillover effects among green bond, renewable energy stocks and carbon markets during COVID-19 pandemic: Implications for hedging and investments strategies. *Global Finance Journal, 51*, Article 100692.

Umar, Z., & Gubareva, M. (2020). A time-frequency analysis of the impact of the Covid-19 induced panic on the volatility of currency and cryptocurrency markets. *Journal of Behavioral and Experimental Finance, 28*, Article 100404. https://doi.org/10.1016/j.jbef.2020.100404

Umar, Z., & Gubareva, M. (2021). Faith-based investments and the Covid-19 pandemic: Analyzing equity volatility and media coverage time-frequency relations. *Pacific-Basin Finance Journal, 67*, Article 101571. https://doi.org/10.1016/j.pacfin.2021.101571

Umar, Z., Gubareva, M., Naeem, M., & Akhter, A. (2021). Return and volatility transmission between oil price shocks and agricultural commodities. *PLoS One, 16*(2), Article e0246886. https://doi.org/10.1371/journal.pone.0246886

Umar, Z., Gubareva, M., & Sokolova, T. (2021c). The impact of the Covid-19 related media coverage upon the five major developing markets. *PLoS One, 16*(7), Article e0253791. https://doi.org/10.1371/journal.pone.0253791

Umar, Z., Gubareva, M., Teplova, T., & Alwahedi, A. (2022). Oil price shocks and the term structure of the US yield curve: A time-frequency analysis of spillovers and risk transmission. *Annals of Operations Research*. https://doi.org/10.1007/s10479-022-04786-1

Umar, Z., Manel, Y., Riaz, Y., & Gubareva, M. (2021). Return and volatility transmission between emerging markets and US debt throughout the pandemic crisis. *Pacific-Basin Finance Journal, 67*, Article 101563. https://doi.org/10.1016/j.pacfin.2021.101563

Umar, Z., Mokni, K., Manel, Y., & Gubareva, M. (2024). Dynamic spillover between oil price shocks and technology stock indices: A country level analysis. *Research in International Business and Finance, 69*, Article 102231. https://doi.org/10.1016/j.ribaf.2024.102231

Umar, Z., Polat, O., Choi, S.-Y., & Teplova, T. (2022). The impact of the Russia-Ukraine conflict on the connectedness of financial markets. *Finance Research Letters*, Article 102976.

Wang, Y., & Guo, Z. (2018). The dynamic spillover between carbon and energy markets: New evidence. *Energy, 149*, 24–33. https://doi.org/10.1016/j.energy.2018.01.145

Wang, X., Li, J., & Ren, X. (2022). Asymmetric causality of economic policy uncertainty and oil volatility index on time-varying nexus of the clean energy, carbon and green bond. *International Review of Financial Analysis, 83*, Article 102306. https://doi.org/10.1016/j.irfa.2022.102306

Wei, Y., Zhang, J., Bai, L., & Wang, Y. (2023). Connectedness among El niño-southern oscillation, carbon emission allowance, crude oil and renewable energy stock markets: Time- and frequency-domain evidence based on TVP-VAR model. *Renewable Energy, 202*, 289–309. https://doi.org/10.1016/j.renene.2022.11.098

Wen, F., Zhao, L., He, S., & Yang, G. (2020). Asymmetric relationship between carbon emission trading market and stock market: Evidences from China. *Energy Economics, 91*. https://doi.org/10.1016/j.eneco.2020.104850

Woerdman, E., & van Zeben, J. (2023). European union emissions trading system (EU ETS). In S. Garben, L. Gormley, & O. Woolley (Eds.), *Oxford encylopedia of EU law (oxford public international law)*. Oxford University Press. https://doi.org/10.1093/law-oeeul/e168.013.168.

Wu, R., Qin, Z., & Liu, B.-Y. (2022). A systemic analysis of dynamic frequency spillovers among carbon emissions trading (CET), fossil energy and sectoral stock markets: Evidence from China. *Energy, 254*. https://doi.org/10.1016/j.energy.2022.124176

Yang, M.-Y., Chen, Z., Liang, Z., & Li, S.-P. (2023). Dynamic and asymmetric connectedness in the global "Carbon-energy-stock" system under shocks from exogenous events. *Journal of Commodity Markets, 32*. https://doi.org/10.1016/j.jcomm.2023.100366

Yousaf, I., Arfaoui, N., & Gubareva, M. (2023). Spillovers and hedging effectiveness between oil and US equity sectors: Evidence from the COVID pre- and post-vaccination phases. *Research in International Business and Finance, 69*, Article 102204. https://doi.org/10.1016/j.ribaf.2023.102204

Yousaf, I., Nekhili, R., & Gubareva, M. (2022). Linkages between DeFi assets and conventional currencies: Evidence from the COVID-19 pandemic. *International Review of Financial Analysis, 81*, Article 102082. https://doi.org/10.1016/j.irfa.2022.102082

Yousaf, I., Qureshi, S., Qureshi, F., & Gubareva, M. (2023). Connectedness of COVID vaccination with economic policy uncertainty, oil, bonds, and sectoral equity markets: Evidence from the US. *Annals of Operations Research*. https://doi.org/10.1007/s10479-023-05267-9

Zhao, L., & Wen, F. (2022). Risk-return relationship and structural breaks: Evidence from China carbon market. *International Review of Economics & Finance, 77*, 481–492. https://doi.org/10.1016/j.iref.2021.10.019

Zheng, Y., Yin, H., Zhou, M., Liu, W., & Wen, F. (2021). Impacts of oil shocks on the EU carbon emissions allowances under different market conditions. *Energy Economics, 104*, Article 105683. https://doi.org/10.1016/j.eneco.2021.105683

Zheng, Y., Zhou, M., & Wen, F. (2021b). Asymmetric effects of oil shocks on carbon allowance price: Evidence from China. *Energy Economics, 97*, Article 105183. https://doi.org/10.1016/j.eneco.2021.105183

Zhu, J. J., Zhang, R., Kanhalikham, K., Liu, Z., & Shen, X. (2023). Green economy studies amongst the global climate change challenge between 2016 and 2022: A bibliometric review. *Frontiers in Ecology and Evolution, 11*, Article 1168437. https://doi.org/10.3389/fevo.2023.1168437