WEP
Warwick
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Publishing

Transactions on Economics, Business and Management Research
ISSN: 2960-1789, eISSN: 2960-2254 | Volume 17
WEPM 2026

Time-Varying Spillovers among Carbon, Oil, and Stock Market Volatility: Evidence from a TVP-VAR-DY Framework

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Abstract. Against the backdrop of global climate governance and increasing financial market integration, understanding the dynamic risk transmission among carbon, energy, and financial markets has become increasingly important. This paper investigates the time-varying volatility spillovers among the international carbon market, the crude oil market, and the Chinese and U.S. stock markets by distinguishing between good and bad volatility. Using monthly data from January 2008 to November 2024 and employing the TVP-VAR-DY connectedness framework, we examine the magnitude, direction, and evolution of volatility spillovers across markets. The empirical results show that the crude oil market consistently acts as a net volatility transmitter under both good and bad volatility systems, while the Chinese and U.S. stock markets mainly serve as net receivers. Moreover, spillovers associated with bad volatility are significantly stronger and more persistent than those associated with good volatility, highlighting the asymmetric nature of cross-market risk transmission. Pairwise connectedness analysis further indicates that the oil market exerts dominant spillover effects on both the carbon market and stock markets, whereas the carbon market transmits risk to the Chinese stock market during certain periods. These findings provide important implications for cross-market risk management, portfolio diversification, and policy coordination in the context of the global low-carbon transition.

Keywords: Carbon market, Crude oil, Stock market volatility, Good and bad volatility, TVP-VAR-DY, Time-varying spillovers.

1. Introduction

Climate change mitigation and the transition toward a low-carbon economy have profoundly reshaped global financial markets. Carbon markets, particularly the European Union Emissions Trading System (EU ETS), have evolved from policy-driven instruments into financially relevant markets that interact closely with traditional energy and financial markets. At the same time, crude oil remains a key driver of global economic activity, and its price volatility has long been recognized as an important source of risk for financial markets. Stock markets, as barometers of economic expectations and investor sentiment, inevitably absorb and transmit shocks originating from energy and environmental markets.

With increasing globalization and financial integration, volatility shocks are no longer confined within individual markets but are transmitted across asset classes and regions. Such spillovers are highly time-varying and often asymmetric, particularly during periods of heightened uncertainty such as financial crises, energy shocks, and major policy changes. Understanding these dynamic and asymmetric spillover mechanisms is therefore crucial for investors seeking effective risk diversification and for policymakers aiming to safeguard financial stability during the low-carbon transition.

This study contributes to the literature in three main aspects. First, it integrates the international carbon market, crude oil market, and the Chinese and U.S. stock markets into a unified analytical framework, highlighting the systemic nature of volatility transmission across energy, environmental, and financial markets. Second, by distinguishing between good and bad volatility, this study uncovers pronounced asymmetries in cross-market spillovers, showing that downside risk dominates volatility transmission. Third, the paper employs the TVP-VAR-DY framework to capture evolving connectedness without relying on arbitrary rolling windows, allowing for a more accurate characterization of spillover dynamics during major economic and energy-related disruptions.

The remainder of the paper is organized as follows. Section 2 reviews the related literature. Section 3 introduces the methodology and data. Section 4 presents and discusses the empirical results. Section 5 concludes with policy and investment implications.

2. Literature Review

A growing body of literature has examined the interactions among carbon, energy, and financial markets. Early studies primarily focused on the determinants of carbon allowance prices, emphasizing the role of energy prices, macroeconomic conditions, and regulatory design. More recent research highlights the increasing financialization of carbon markets and their exposure to external financial shocks.

The crude oil market has been widely documented as a major source of volatility spillovers to financial markets. Oil price shocks influence stock market volatility through channels such as production costs, inflation expectations, and investor sentiment, especially during periods of economic stress.

From a methodological perspective, Diebold and Yilmaz (2009, 2012, 2014) propose a spillover index based on forecast error variance decompositions from VAR models, which has become a standard tool for measuring market connectedness. Antonakakis et al. (2020) extend this framework by introducing a time-varying parameter VAR model, allowing spillover measures to evolve smoothly over time.

Another strand of the literature emphasizes asymmetry in volatility transmission by decomposing volatility into good and bad components. These studies generally find that negative shocks generate stronger and more persistent spillovers than positive shocks, reflecting heightened risk aversion during downturns. Despite these advances, relatively few studies integrate carbon, oil, and stock markets within a unified time-varying and asymmetric framework, which this paper aims to address.

3. Methodology and Data

3.1. Methodology

This study adopts the Time-Varying Parameter Vector Autoregression (TVP-VAR) connectedness framework proposed by Antonakakis et al. (2020), which extends the spillover index methodology developed by Diebold and Yilmaz. The TVP-VAR model allows coefficients and variance–covariance matrices to evolve smoothly over time and is estimated using the Kalman filter. This approach avoids the limitations associated with rolling-window VAR models, such as arbitrary window selection and information loss.

Based on the estimated TVP-VAR model, generalized forecast error variance decompositions are computed to construct measures of total, directional, and net connectedness. A positive net connectedness value indicates that a market acts as a net transmitter of volatility, whereas a negative value implies that it is a net receiver.

To capture asymmetric spillover effects, volatility is decomposed into good and bad components following the realized semi-variance approach. Separate TVP-VAR-DY models are estimated for good and bad volatility systems, enabling a comparison of spillover dynamics under favorable and adverse market conditions.

3.2. Data

The international carbon market is proxied by European Union Allowances (EUA), the crude oil market by West Texas Intermediate crude oil prices (NYMEX), the Chinese stock market by the Shanghai Composite Index (SZ), and the U.S. stock market by the S&P 500 Index (SP500). Monthly data from January 2008 to November 2024 are employed, covering major global events such as the global financial crisis and the COVID-19 pandemic.

3.3. Descriptive Statistics

Table 1 reports the descriptive statistics of realized volatility (RV), good realized volatility (GVR), and bad realized volatility (BVR) for the crude oil market (NYMEX), the international carbon market (EUA), the U.S. stock market (S&P 500), and the Chinese stock market (SZ). Several stylized facts can be observed.

First, across all markets, bad volatility exhibits higher mean values than good volatility, indicating that downside risk constitutes a dominant component of total volatility. This pattern is particularly pronounced in the crude oil and carbon markets, suggesting that adverse shocks play a more important role than positive shocks in driving volatility dynamics in energy and environmental markets.

Second, the crude oil market displays the largest volatility magnitude, as reflected by its higher mean, maximum, and standard deviation across RV, GVR, and BVR measures. This finding is consistent with the role of oil as a globally traded commodity that is highly sensitive to geopolitical tensions, supply disruptions, and macroeconomic uncertainty. In contrast, stock markets—especially the Chinese stock market—exhibit relatively lower volatility levels, reflecting differences in market structure and regulatory environments.

Third, all volatility measures are highly right-skewed and leptokurtic, with skewness significantly greater than zero and kurtosis far exceeding the benchmark value of three. This indicates the presence of extreme observations and fat tails, implying that volatility shocks are infrequent but severe. Such distributional characteristics provide strong motivation for adopting a connectedness framework capable of capturing tail-risk transmission.

Finally, the augmented Dickey–Fuller (ADF) test results reject the null hypothesis of a unit root at the 1% significance level for all series, confirming that the volatility measures are stationary. This ensures the validity of the TVP-VAR estimation and supports the subsequent spillover analysis.

Table 1. Descriptive Statistics

	Mean	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	ADF
RVNYMEX	0.0163	0.4756	0.0007	0.0409	8.3537	85.3911	-8.6152***
RVEUA	0.0193	0.2630	0.0015	0.0260	5.0333	40.9181	-8.5125***
RVSP500	0.0033	0.0725	0.0001	0.0080	7.0015	57.8846	-8.8840***
RVSZ	0.0044	0.0317	0.0002	0.0057	2.6462	10.0967	-7.1490***
GVRNYMEX	0.0073	0.1959	0.0002	0.0170	8.2315	83.7021	-6.6476***
GVREUA	0.0088	0.0636	0.0003	0.0101	2.8154	12.5879	-6.3692***
GVRSP500	0.0015	0.0272	0.0001	0.0032	5.9088	43.3561	-8.2782***
GVRSZ	0.0020	0.0156	0.0000	0.0026	2.9545	12.8903	-4.2041***
BVRNYMEX	0.0090	0.2987	0.0001	0.0264	8.5440	85.2486	-8.8803***
BVREUA	0.0105	0.2301	0.0001	0.0200	7.2684	74.3135	-11.5681***
BVRSP500	0.0018	0.0453	0.0000	0.0047	6.4816	50.0112	-9.2506***
BVRSZ	0.0024	0.0238	0.0000	0.0039	3.2427	14.3366	-9.5090***

4. Empirical Results and Discussion

4.1. Analysis Based on Overall Realized Volatility

The time-varying trajectory of the total connectedness index reveals that the intensity of risk contagion within the system is not constant but fluctuates sharply in response to major macroeconomic events. Following the 2008 global financial crisis, the index remained at an elevated level, before entering a relatively tranquil "calm period" between 2013 and 2019, during which overall connectedness stabilized at a lower level. However, the global market panic triggered by the COVID-19 pandemic in 2020 caused the index to skyrocket to its sample-period peak. This clearly demonstrates that extreme external shocks can rapidly strengthen cross-market risk linkages and synchronize volatility across different asset classes. The subsequent decline in the index reflects the post-crisis recovery process, as policy interventions were implemented and markets gradually adapted.

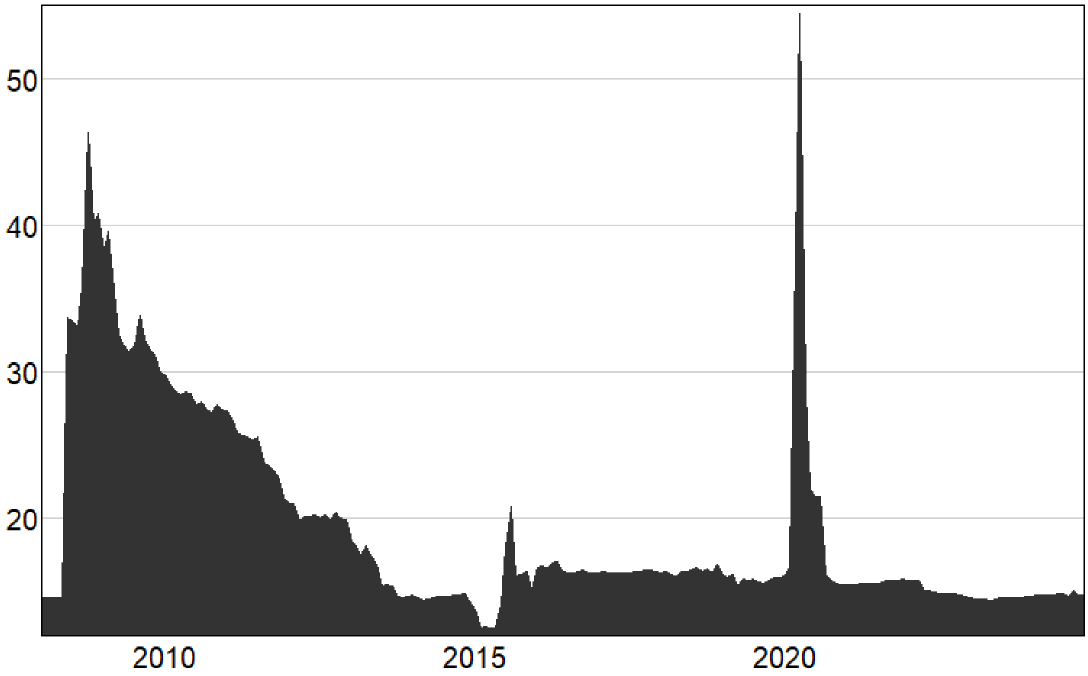

Fig. 1 Total RV Connectedness

From the perspective of "spillovers to other markets" (TO), the U.S. S&P 500 index exhibited an exceptionally strong capacity for risk transmission at the beginning of the sample period (2010), with its TO value reaching as high as 93, far exceeding that of other markets. This reaffirms its status as the primary source of volatility within the global financial system. However, this influence displayed a clear and consistent declining trend over the years, with its TO value dropping to 11 by 2020. This indicates that although U.S. stocks remained net transmitters, the absolute intensity of their outward risk radiation weakened significantly over the past decade, possibly reflecting the evolution of global market structures or the enhancement of endogenous stability in other markets. In contrast, the TO values for China's Shanghai Composite Index remained at very low levels throughout (peaking at 12.5 and reaching 1 in 2020), visibly demonstrating the weakness of its outward spillover effects. The TO values for the carbon market (EUA) and the crude oil market (NYMEX) occupied an intermediate range and also declined gradually over time, suggesting that their influence as secondary sources of volatility was not constant.

From the perspective of "spillovers from other markets" (FROM), the external risk shocks received by each market also followed distinct evolutionary paths. Most notably, the external spillovers received by the U.S. S&P 500 index (FROM value) decreased sharply from 17.5 in 2010 to 4.5 in 2020, representing a significant decline. This implies that the influence of external market fluctuations on U.S. stocks has substantially diminished, with the sources of their volatility becoming increasingly endogenous and their independence strengthened. Although the FROM value for China's Shanghai

Composite Index also declined from 12.5 to 9.0, the decrease was relatively moderate. Furthermore, its absolute value consistently remained higher than its own TO value throughout the entire sample period, which reconfirms from the receiving end its stable role as a "net risk receiver." The FROM values for the carbon and crude oil markets, however, were remarkably stable, fluctuating only slightly around 4.5. This indicates that the intensity of systemic risk input they received was relatively constant and less affected by changes in the overall market environment.

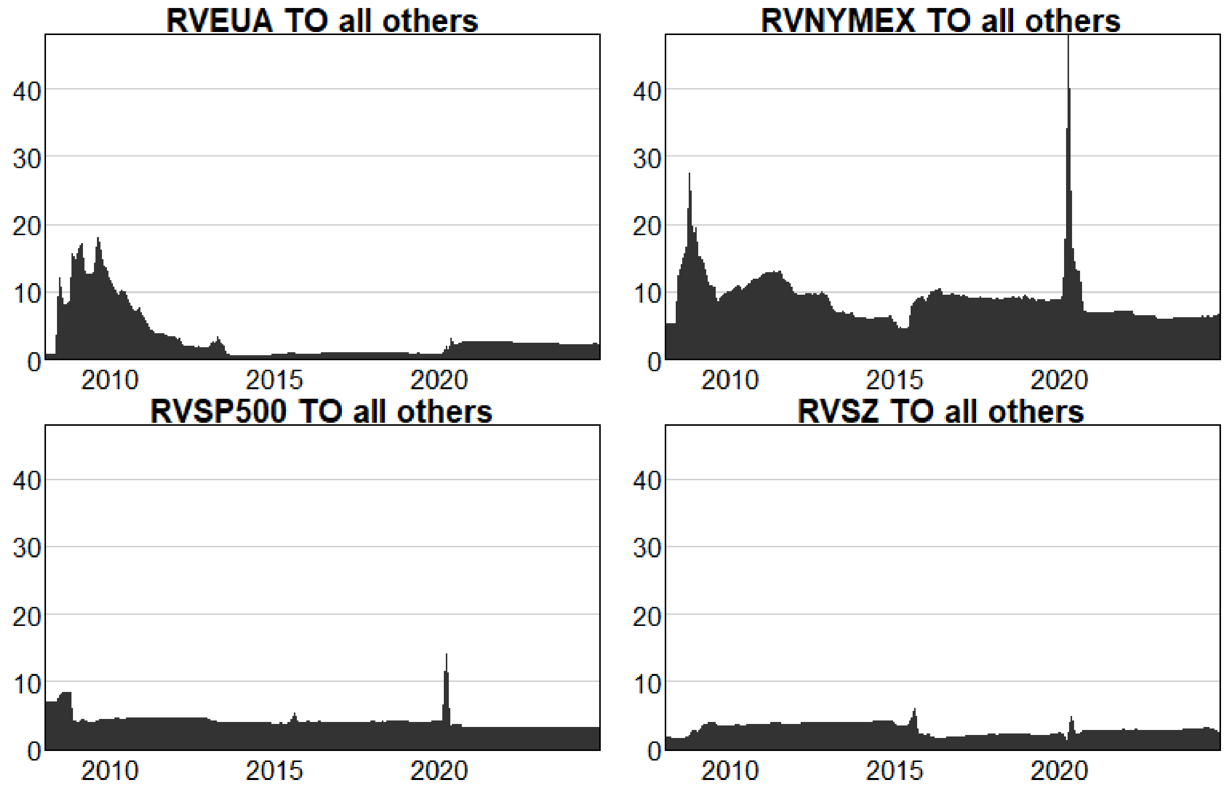

Fig. 2 RV Spillovers TO Others

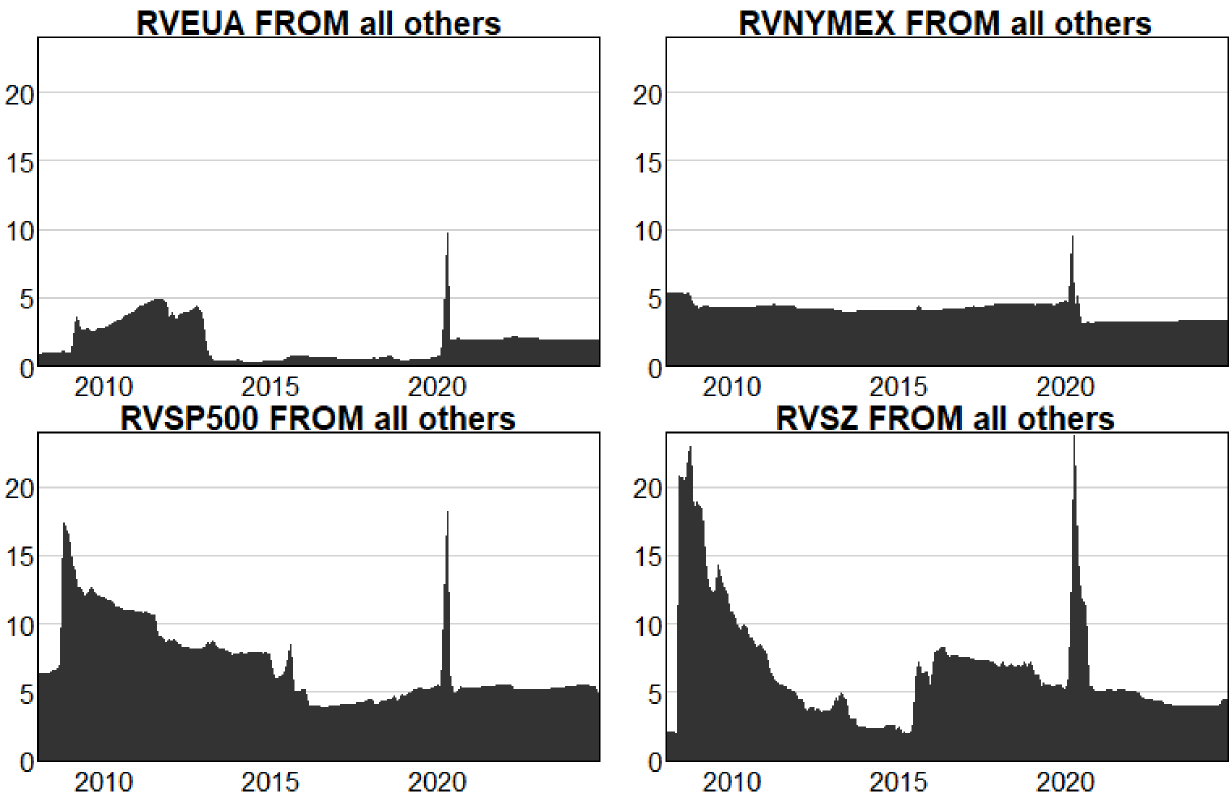

Fig. 3 RV Spillovers FROM Others

At the level of realized volatility (RV), the U.S. S&P 500 index is not a net transmitter of systemic risk but rather a persistent and significant net receiver. Its net spillover values remained consistently negative throughout the 2010–2020 period, reaching a peak of -5 during the European debt crisis in 2011–2012—indicating the highest intensity of risk inflow—and subsequently moderating yet stabilizing around a negative range of approximately -1. This suggests that although fluctuations in U.S. stocks have a substantial impact on global markets (as reflected in high TO values), a considerable portion of their own volatility is driven by other markets within the system. In net terms, their role is characterized by receiving more than transmitting.

In the early part of the sample period (2010–2011), the carbon and crude oil markets indeed served as the primary net transmitters of systemic risk. Their notably high positive net spillover values—such as 12 for EUA and 22 for NYMEX in 2010—confirm their role as key sources of risk during that phase. However, this dominant position was short-lived. The net spillover values for both markets declined sharply from 2012 onward and approached zero after 2014, transitioning into neutral nodes. In contrast, the net spillover values for China's stock market remained the most deeply negative throughout the sample period, underscoring its role as the "core net receiver," which is both more pronounced and more stable than that of U.S. stocks.

The pairwise net spillover data precisely delineates the key pathways of risk transmission and fully aligns with the interpretation above. First, there is a persistent positive net spillover from the crude oil market to the carbon market (RVNYMEX – RVEUA is consistently positive), establishing a clear oil-to-carbon transmission axis. Second, the net spillovers from both the carbon and crude oil markets to China's stock market are strongly negative with large absolute values, confirming that the net flow of risk from these two commodity markets is directed toward China's equities, with significant shock intensity. Most importantly, the net spillover from China's stock market to the U.S. stock market (RVSZ – RVSP500) is also consistently negative, clearly indicating that, in the bilateral relationship, the net direction of risk flows from the U.S. stock market to China's stock market. This is fully consistent with the net spillover index, where both markets show negative values (both are net receivers), yet the A-share market exhibits deeper negative values (greater net receiving intensity), revealing a clear, asymmetric structure of one-way risk transmission from U.S. stocks to A-shares.

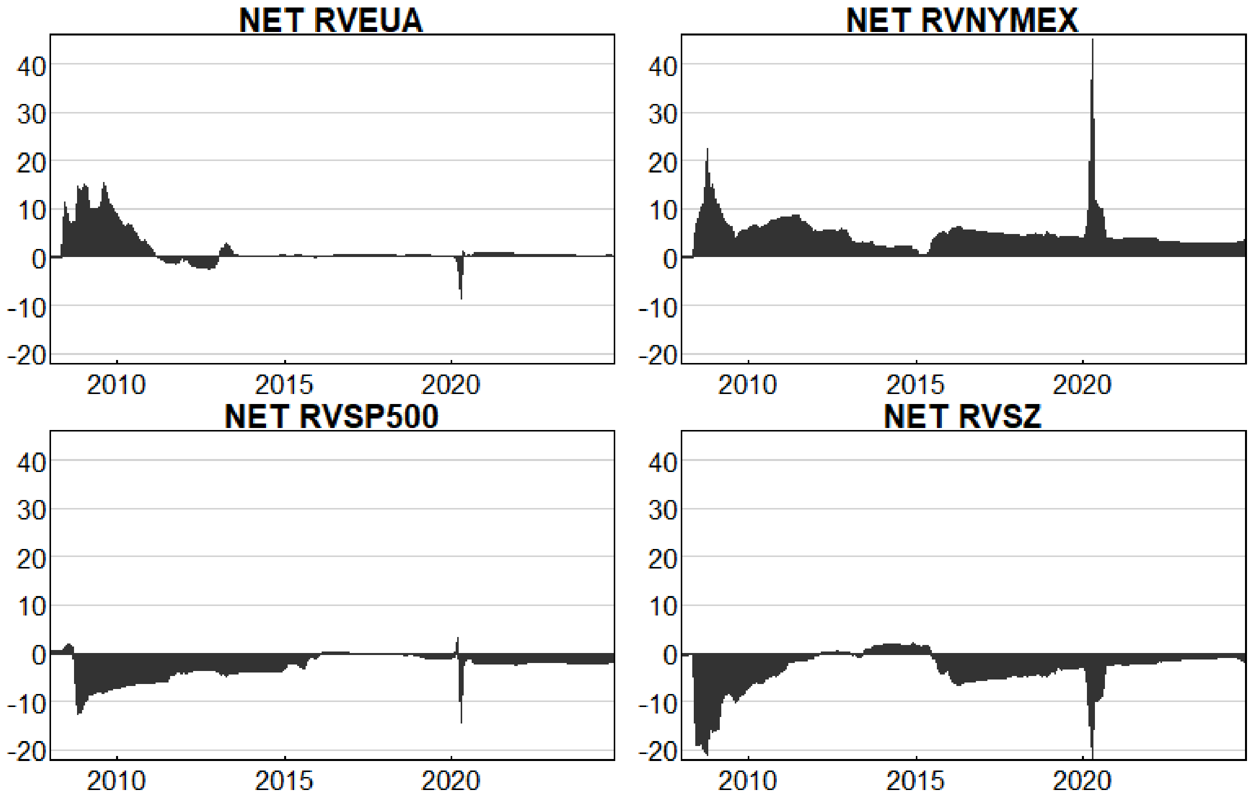

Fig. 4 RV Net Spillover

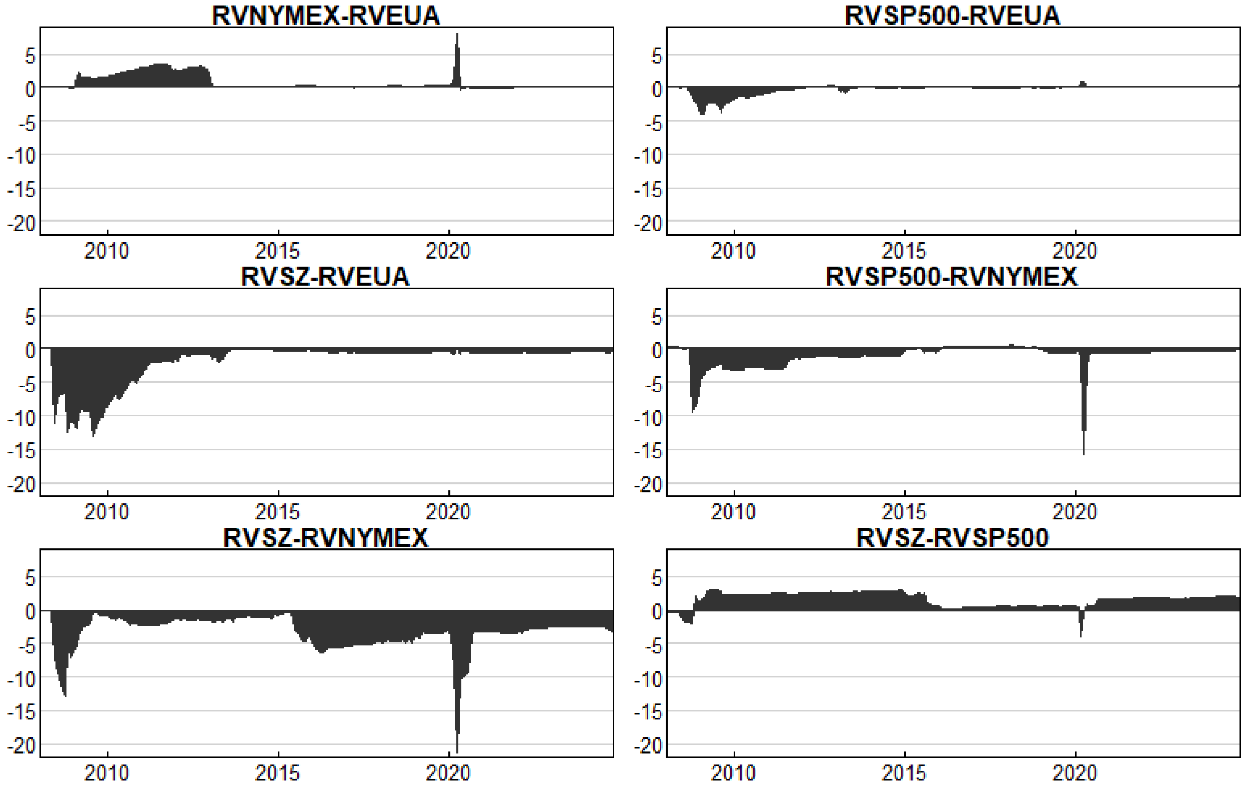

Fig. 5 RV Pairwise Spillover

Based on the empirical analysis of realized volatility (RV), a risk spillover network with an asymmetric hierarchical structure exists among the carbon market (EUA), crude oil market (NYMEX), U.S. stock market (SP500), and Chinese stock market (SZ). Within this network, both the U.S. and Chinese stock markets act as net risk receivers, with the Chinese market particularly standing out as a systemic "risk sink." In contrast, the crude oil and carbon markets served as key net risk transmitters in the early part of the sample period, though their influence diminished rapidly thereafter, transforming them into neutral transmission nodes. Risk spillovers primarily flow along three directional channels: stable spillovers from the crude oil to the carbon market, strong shocks from the commodity markets to the Chinese stock market, and a unidirectional hierarchical transmission from the U.S. stock market to the Chinese stock market. This structure clearly reveals the sources, main convergence points, and critical connectivity channels of cross-market risk transmission, providing important insights for understanding the risk linkages between financial and commodity markets.

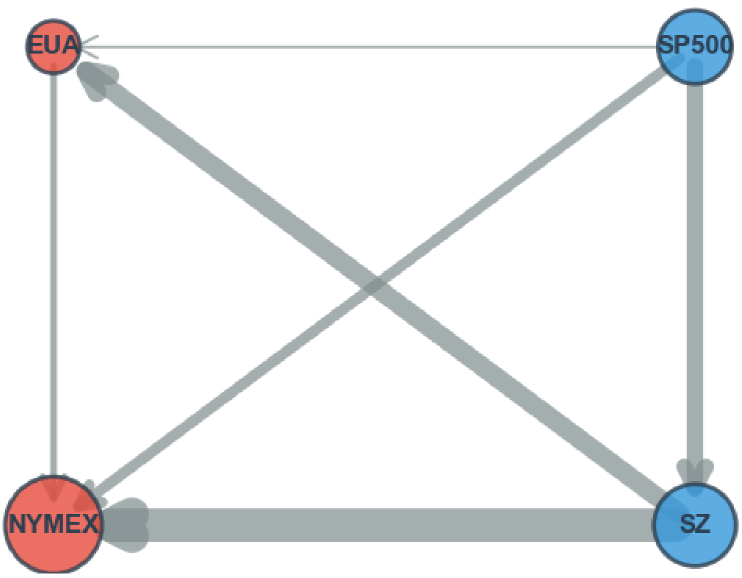

Fig. 6 RV Spillover Network

4.2. Analysis Based on Good Realized Volatility

The total connectedness index constructed based on good volatility (GRV) reveals the dynamic characteristics of the transmission of positive volatility or "favorable sentiment" across markets. The index exhibits distinct phase changes over the sample period. Following the 2008 global financial crisis, the index remained at a relatively high level (46.0 in 2009), reflecting synchronized market reactions to positive signals during the early recovery phase. Subsequently, the index entered a prolonged downward trend, steadily declining from 36.0 in 2010 to 11.0 in 2020. This trend suggests that in a relatively stable macroeconomic environment, the co-movement of positive volatility across markets gradually weakened, and the responses of individual markets to favorable news became more independent.

However, this trend underwent a fundamental reversal in 2021, when the index sharply surged to 38.0, forming a prominent peak. This timing coincides precisely with the period when major global economies launched large-scale green recovery plans, reinforced carbon neutrality commitments, and expectations for clean energy transition reached a climax. This indicates that strong, coherent policy signals and transition narratives can rapidly reshape the network of optimistic sentiment among markets, leading to strong coordinated movements in positive volatility across the carbon market, energy markets, and equity markets, resulting in a concentrated contagion of "green optimism." Thereafter, the index moderated in 2022–2024 but remained significantly higher than its 2020 low, stabilizing within the range of 17.0–19.0. This implies that the positive linkages triggered by climate issues have established a new, higher baseline level of stability compared to the previous period.

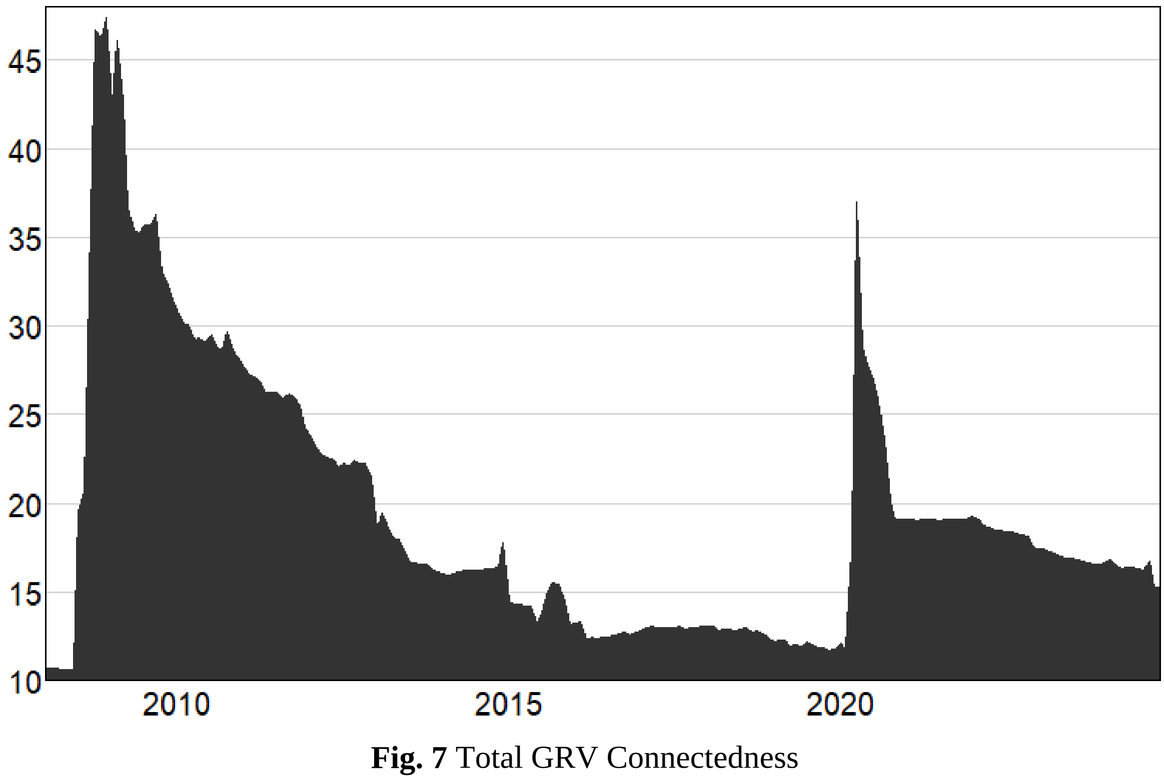

Fig. 7 Total GRV Connectedness

Based on the directional connectedness data of good volatility (GRV), we conducted an in-depth analysis of the evolving roles of each market within the positive volatility transmission network. From the perspective of “spillovers to other markets” (TO), both the carbon market (EUA) and the crude oil market (NYMEX) exhibited a strong capacity to transmit positive sentiment in the early sample period (2010–2011), with TO values as high as 24.5 and 23.0, significantly exceeding those of U.S. stocks (SP500) and A-shares (SZ). This clearly indicates that during the early phase of rising green transition expectations, optimistic signals stemming from energy and climate policies were primarily generated and radiated outward by commodity markets. However, this dominant position diminished rapidly, as the TO values of both markets dropped substantially after 2013 and stabilized at a lower range of 2.0–5.0, suggesting that their role as core sources of positive volatility was not long-lasting.

Examining the "spillovers from other markets" (FROM) perspective reveals key structural characteristics on the receiving side. The U.S. S&P 500 index was the primary receiver of positive volatility in the system throughout the early sample period (2010–2012), with its FROM value reaching as high as 20.0, far above its own TO value (4.5). This highlights a core finding: in the GRV dimension, the role of U.S. stocks undergoes a fundamental reversal—it is not a net transmitter of positive sentiment but rather the foremost **net receiver and absorber**. This implies that "good news" sentiment from global markets ultimately converges and is largely priced into U.S. equities. China's stock market (SZ) was also a significant receiver of positive volatility in the early stage (with a FROM value peaking at 22.0), though the decline in its reception intensity over time was somewhat slower than that of U.S. stocks.

Integrating the dynamics of TO and FROM, the GRV network depicts a transmission picture distinctly different from that of the RV network: the "engine" of positive volatility was located on the commodity side (EUA, NYMEX) in the early period, while its most important "convergence point" and "value realization hub" lay on the financial side (especially SP500). Over time, the driving force from the commodity side weakened rapidly, and the overall level of positive volatility co-movement across the network declined, with each market reacting more independently to favorable news. This finding underscores the asymmetry in market sentiment transmission: the transmission of panic (RV) is characterized by strong financial dominance and one-way outward spillovers, whereas the transmission of optimism (GRV) follows a distinct pattern—initiated from the commodity-policy side and converging toward and being absorbed by financial markets.

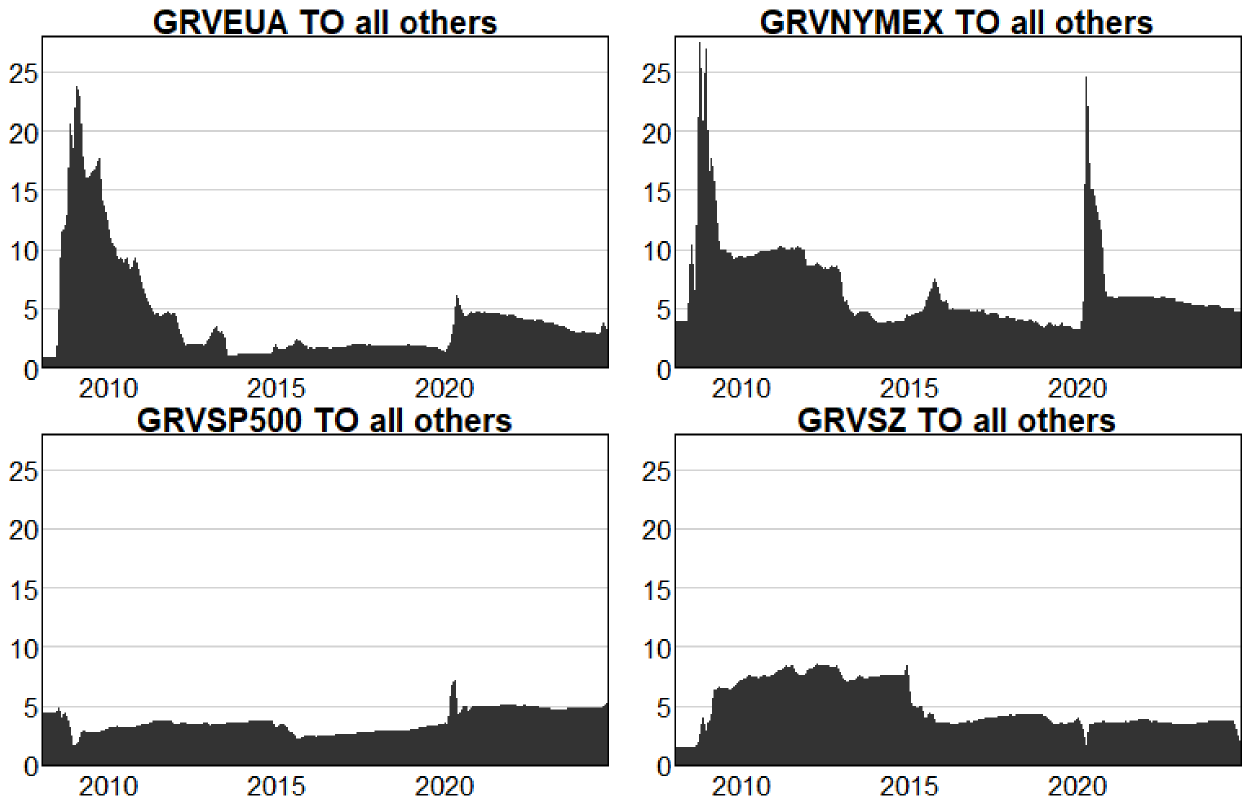

Fig. 8 GRV Spillovers TO Others

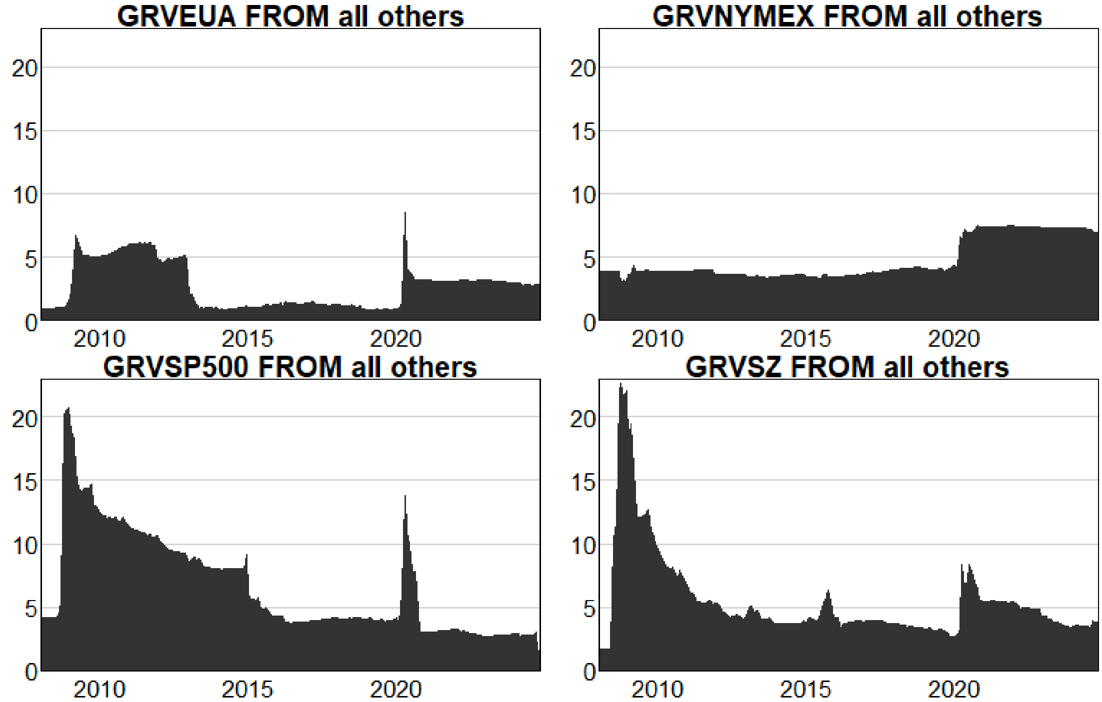

Fig. 9 GRV Spillovers FROM Others

Based on the net spillover data, the role of each market within the good volatility (GRV) network exhibits pronounced time-varying characteristics. In the early sample period, specifically from 2010 to 2012, both the carbon market (EUA) and the crude oil market (NYMEX) functioned as significant net transmitters of positive volatility, with their net spillover values reaching as high as 20.0 and 22.0, respectively. This indicates that during the initial phase of rising green transition expectations, optimism primarily originated from and was radiated by these commodity markets. However, this role was transient; their net spillover intensity decayed rapidly, approaching neutral levels after 2013. In contrast, the U.S. S&P 500 index consistently acted as the dominant net receiver throughout the entire period, with its net spillover values remaining deeply negative (between -4.0 and -18.0). This stable role highlights that U.S. equities served as the ultimate absorber and pricing ground for global positive sentiment within the GRV network, rather than as a source of diffusion.

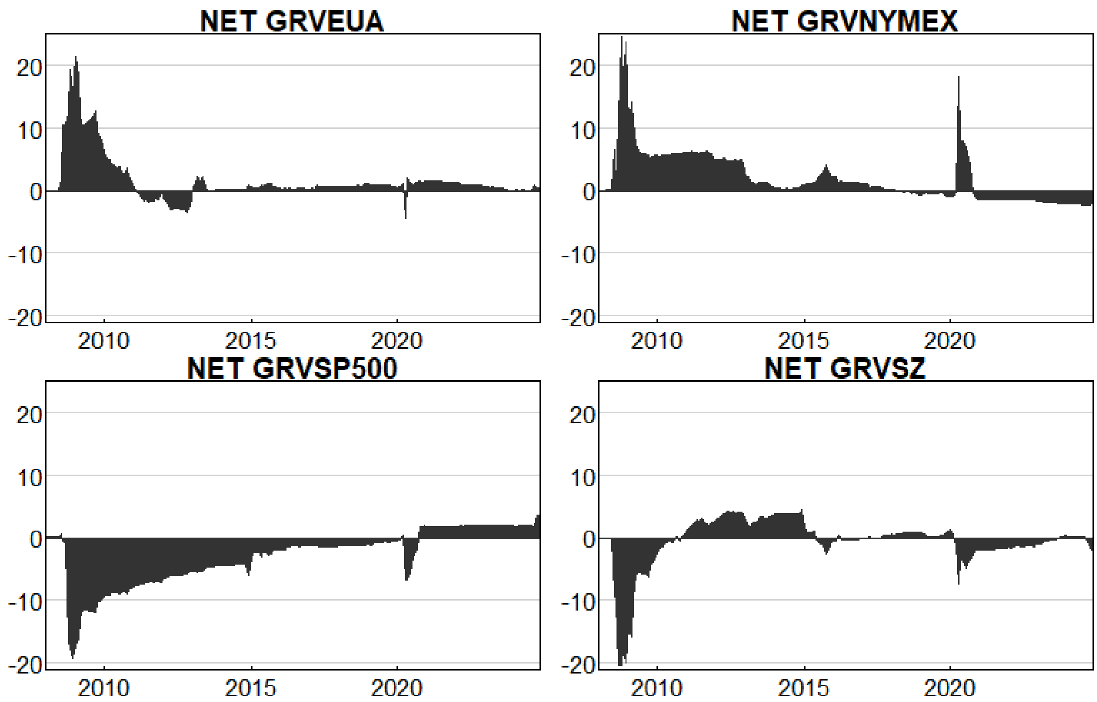

Fig. 10 GRV Net Spillover

The pairwise net spillover analysis further clarifies the specific directional pathways of positive volatility transmission. A persistent and stable positive spillover is observed from the crude oil market to the carbon market, confirming a robust “oil-to-carbon” optimism channel. More notably, the pairwise data reveals a consistent positive net spillover from the Chinese stock market (SZ) to the U.S. stock market (SP500). This indicates that, within this bilateral relationship, positive volatility flowed net from Chinese equities to U.S. equities. This finding nuances the interpretation drawn from the aggregate net spillover figures: although the U.S. market was the system’s largest net receiver overall, it specifically received positive shocks from the Chinese market in a direct pairwise context. Meanwhile, both commodity markets exhibited strong negative net pairwise spillovers toward the Chinese market, underscoring their role as significant sources of positive shocks for Chinese equities in the early period.

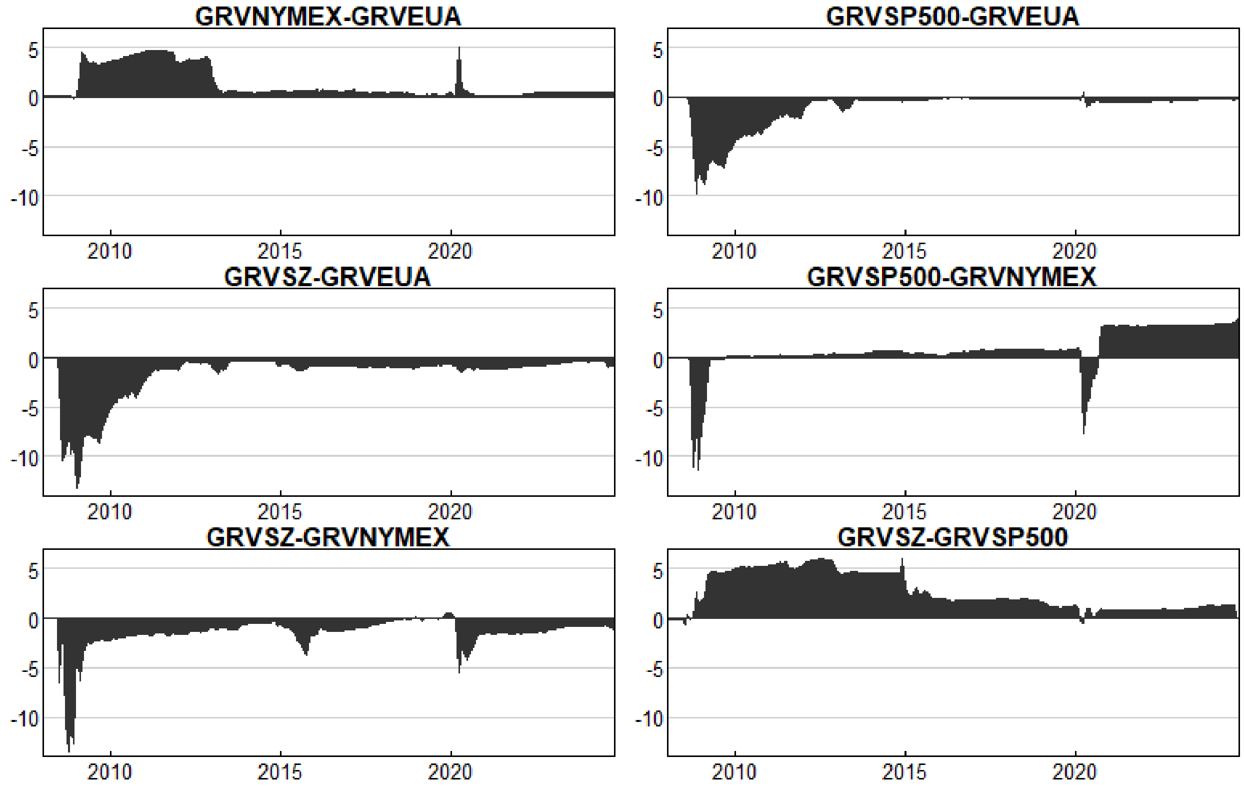

Fig. 11 GRV Pairwise Spillover

Integrating the directional spillover data with the network diagram, which uses red and blue to denote net transmitters and receivers, the structural evolution of the GRV network becomes clear. In the early phase, the network was characterized by two red hubs (EUA and NYMEX) radiating positive volatility via strong outward connections, primarily toward the blue hub (SP500). Over time, as the net spillover capacity of the commodity markets faded—symbolized by their red coloration diminishing—the network structure simplified. It gradually transformed into a system centered on the deep blue node (SP500), which remained the primary convergence point for positive sentiment even as the strength of incoming connections weakened. This dynamic shift from a commodity-driven transmission structure to a finance-centered absorption structure visually encapsulates the unique lifecycle of positive volatility spillovers, distinguishing it fundamentally from the panic-driven, financially centered diffusion observed in the RV network.

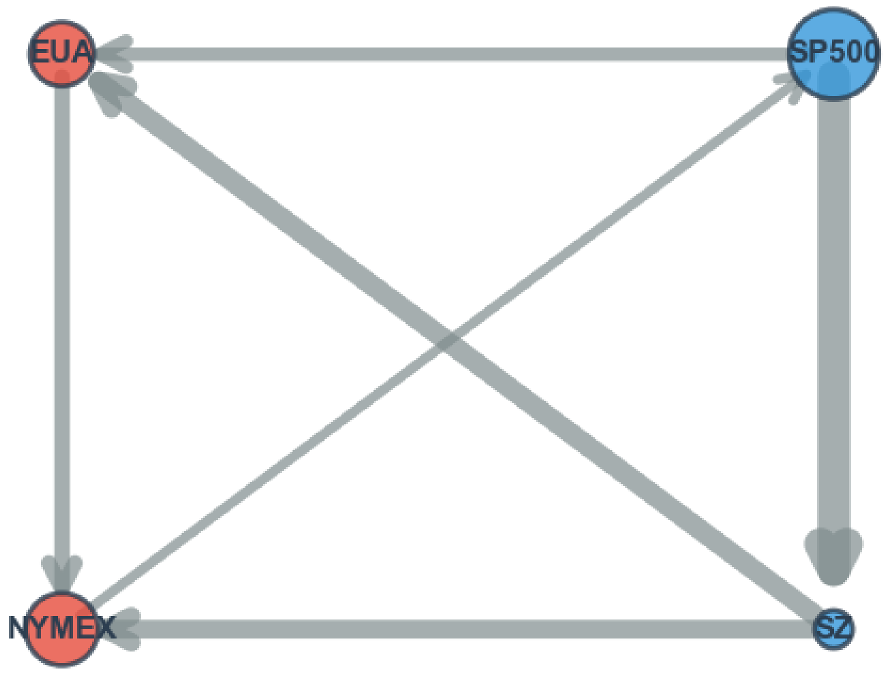

Fig. 12 GRV Spillover Network

4.3. Analysis Based on Bad Realized Volatility

Based on the total connectedness index constructed from bad volatility (BRV), this analysis reveals the dynamic trajectory of downside risk or "negative sentiment" contagion across markets. Following the 2008 global financial crisis, the index remained at a high level of 33.5, after which it exhibited a prolonged and gradual declining trend until it dropped to 16.0 in 2020. This extended attenuation suggests that the co-movement intensity of systemic downside risks gradually weakened during the post-crisis market recovery and policy normalization, with market reactions to negative shocks becoming increasingly differentiated. However, a notable reversal occurred in 2021, when the index rebounded to 30.0, forming a local peak. This coincides closely with the macroeconomic environment marked by a confluence of complex negative shocks in the post-pandemic era—including supply chain disruptions, surging inflationary pressures, and a shift toward monetary policy tightening by major central banks. It indicates that when multiple uncertainties converge, market pessimism resynchronizes, leading to a renewed widespread contagion of downside risks across markets.

What is particularly noteworthy is the evolution after 2021. Instead of lingering at elevated levels, the index plunged sharply to 8.0 in 2022 and remained at this historically low range of 8.0 in the following two years. This cliff-like decline and sustained low level may reflect deeper structural changes in market dynamics. On one hand, it could signify enhanced adaptability of individual markets to known types of shocks (such as inflation and tightening policies), thereby reducing the resonance effect of risks. On the other hand, it may suggest a structural shift in risk transmission mechanisms—for instance, risks being increasingly absorbed within regional markets or specific sectors rather than being diffused globally through traditional major channels like U.S. equities or crude oil. This unique trajectory of BRV total connectedness—characterized by a long-term gradual decline post-crisis, a brief rebound under multiple shocks, followed by a rapid and persistent drop to a low plateau—differs from the patterns observed in both RV and GRV. It underscores the complexity and potential episodic breakdown of downside risk contagion mechanisms in recent years, offering a new empirical perspective for understanding the evolution of extreme risks within global market networks.

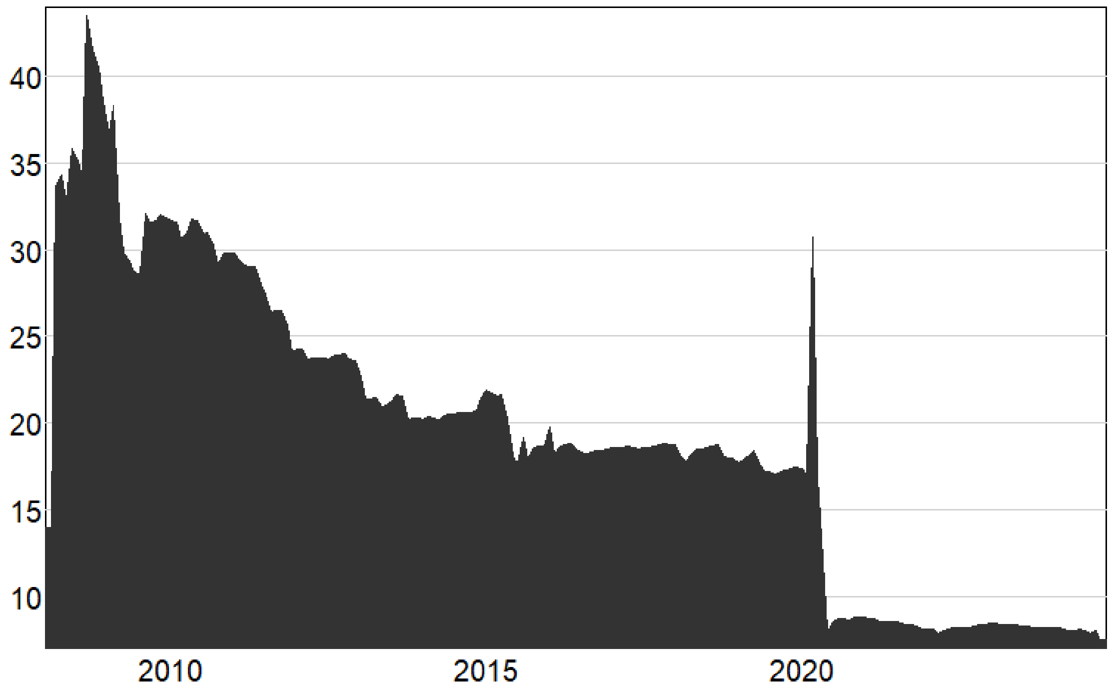

Fig. 13 Total BRV Connectedness

Based on the directional connectedness data of bad volatility (BRV), we conducted an in-depth analysis of the roles of each market within the downside risk transmission network. From the perspective of "spillovers to other markets" (TO), the pattern in the early sample period (2010–2011) clearly indicates that the crude oil market (NYMEX) and the carbon market (EUA) were the primary sources of bad volatility in the system, with TO values as high as 18.0 and 10.5, respectively, significantly exceeding those of the U.S. stock market (SP500) and the Chinese stock market (SZ). This confirms that during the aftermath of a crisis or under major negative shocks, commodity markets often serve as the origin and primary diffusion points for downside risks. However, this pattern did not persist; the TO values of all markets exhibited a systematic decline over time. By the later sample period (2020), the TO values for SP500 and SZ had fallen to nearly zero, indicating that they almost ceased to transmit downside risks externally. Although the TO values for commodity markets also declined substantially, they remained at low positive levels, suggesting that their nature as potential risk sources persisted, albeit at a greatly reduced intensity.

From the perspective of "spillovers from other markets" (FROM), the characteristics on the receiving side reveal the evolution of risk convergence points. The U.S. S&P 500 index was the most prominent receiver of downside risks in the early sample period, with its FROM value reaching 17.5 in 2010, far exceeding that of other markets. This indicates that in the immediate aftermath of the crisis, U.S. stocks bore substantial negative shock pressure from other parts of the system. However, its FROM value subsequently declined continuously and rapidly, falling to 4.5 by 2020, meaning the intensity of external downside risk shocks on U.S. stocks significantly eased. The FROM value of the Chinese stock market (SZ), in contrast, demonstrated remarkable stability, consistently fluctuating around 5.5 with minor variations. This shows that the intensity of external downside risk inflows it received remained relatively constant and did not decline as markedly as that of U.S. stocks, making SZ a relatively more prominent risk-receiving node in the later sample period. The FROM values for the carbon and crude oil markets also remained stable and relatively low, indicating that the external downside risk shocks they received were consistently limited.

Integrating the dynamics of TO and FROM, the BRV network depicts a shifting landscape of risk transmission focus: In the early stage, downside risks were primarily transmitted from commodity markets (NYMEX, EUA) and converged mainly in the U.S. stock market (SP500). Over time, however, the risk-transmitting capacity of commodity markets and the risk-receiving intensity of U.S. stocks weakened substantially in parallel. Meanwhile, the role of the Chinese stock market (SZ) as a "stable receiver" became relatively more pronounced. This evolution aligns with the phenomenon of the total BRV connectedness index plunging to extremely low levels in the later period (post-2022). Together, they may point to a structural change: the effectiveness of the traditional core downside risk transmission channel from commodity markets to U.S. stocks significantly declined in the later sample period, while downside risks may have become more dispersed within the system or transmitted through other pathways not captured in this network, leading to a historically low level of observable directional spillover intensity.

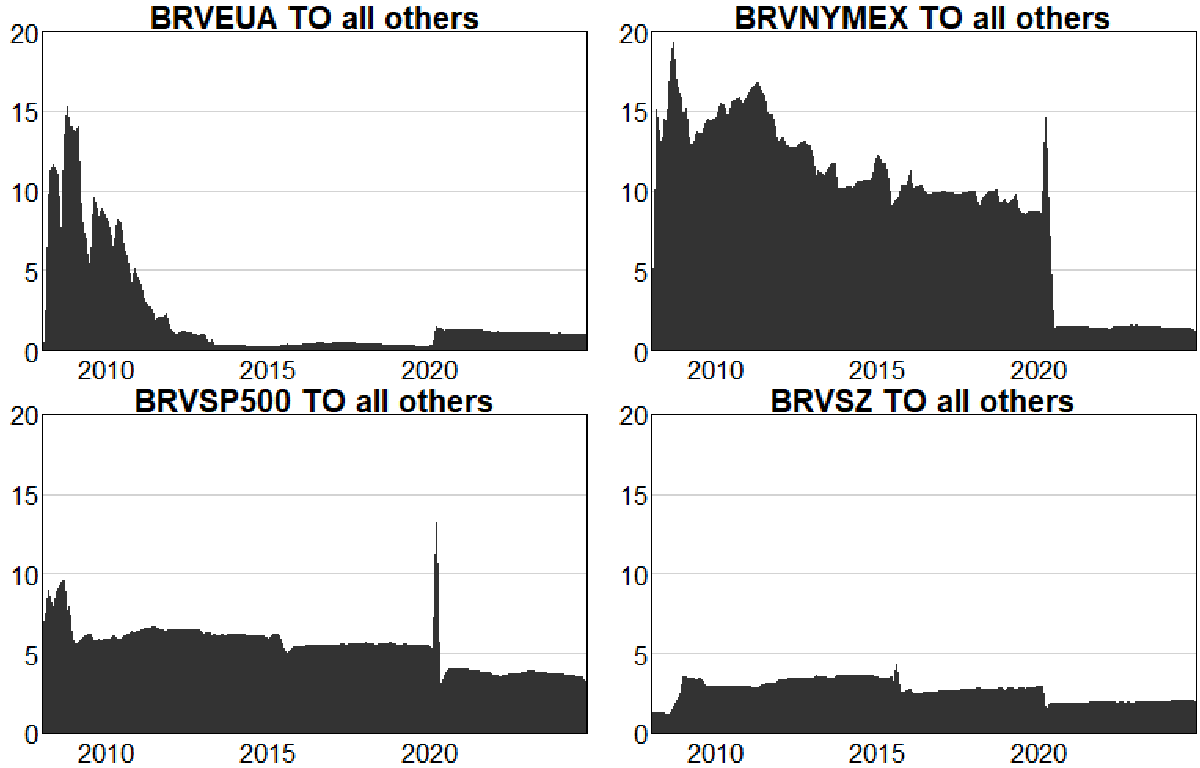

Fig. 14 BRV Spillovers TO Others

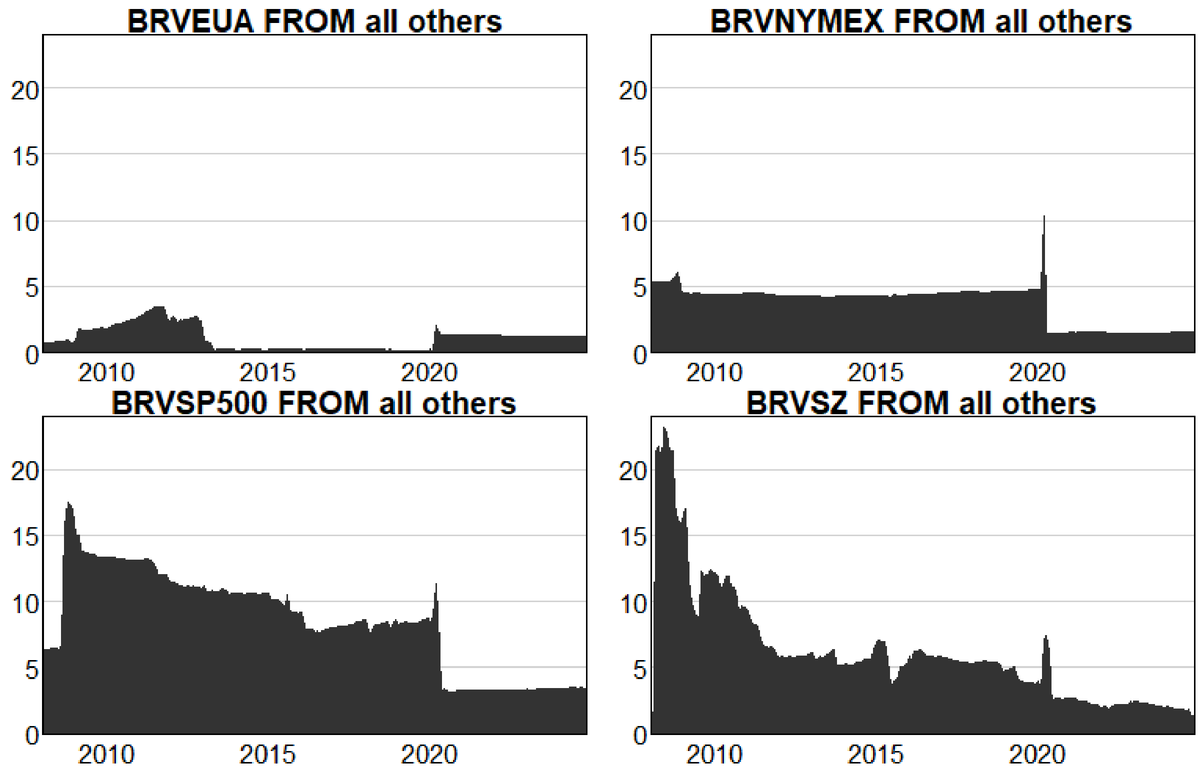

Fig. 15 BRV Spillovers FROM Others

Based on the net spillover and pairwise spillover data of bad volatility (BRV), along with the visualization rules of the network diagram, the dynamic structure and evolution of market roles in the downside risk transmission network become clearly apparent. The net spillover data reveal that in the early sample period, the carbon market and the crude oil market acted as the most prominent net transmitters of downside risk in the system. Their net spillover values reached 10.5 and 12.5, respectively, in 2010, forming powerful red risk sources in the network. However, the net output intensity of both markets plummeted sharply, approaching zero after 2014. In the network diagram, this is reflected as a process where the red color rapidly fades and the circles shrink significantly. At the same time, the net spillover role of the U.S. S&P 500 index underwent a complex transition—from a mild net transmitter to a net receiver and then to a neutral node. Its net value shifted from positive in the early stage to ultimately zero, which in the network may correspond to a color change from light red to pale blue and then to neutral. The most stable role is that of the Chinese stock market, whose net spillover values remained negative throughout the entire sample period. Although the absolute values narrowed, it consistently maintained the clearest position as a net receiver in the system, which should appear as a persistently blue node in the diagram.

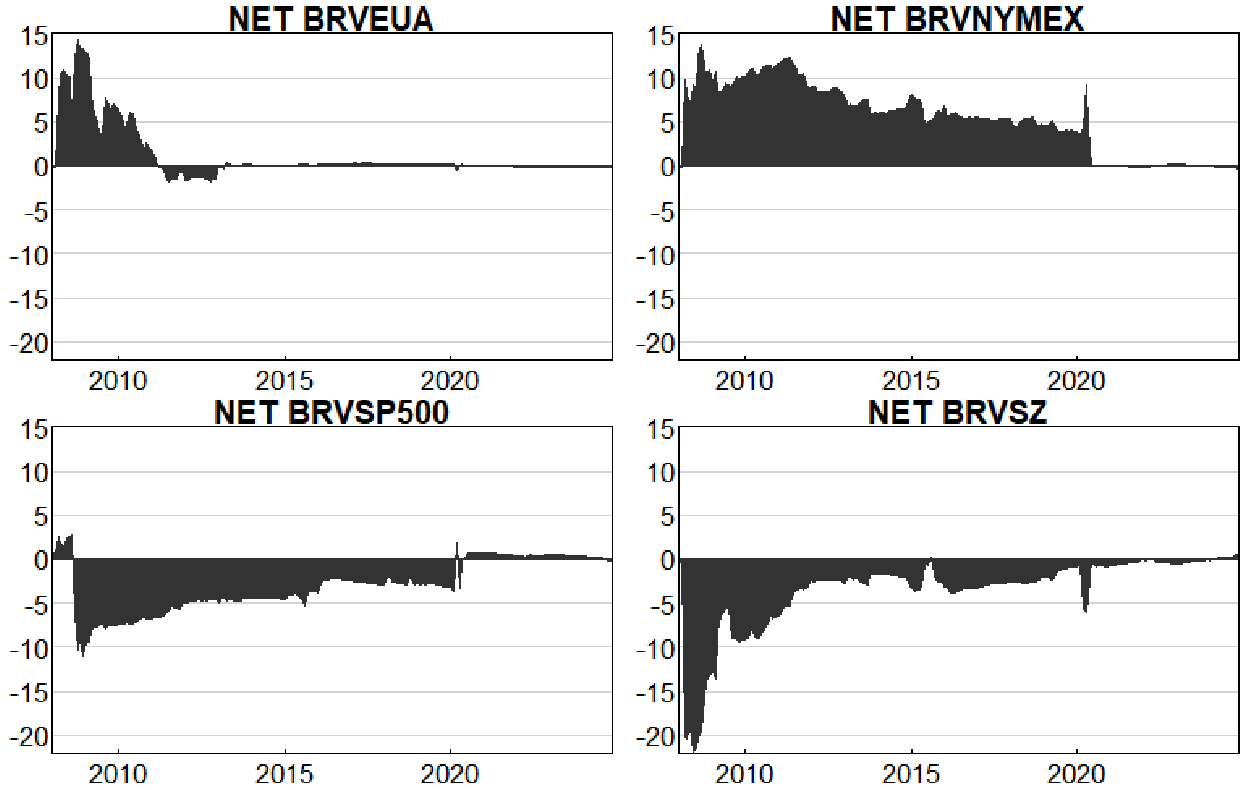

Fig. 16 BRV Net Spillover

The pairwise net spillover data further delineate the specific pathways and relative intensities of risk flow. There is a sustained positive net spillover from the crude oil market to the carbon market, albeit with moderate strength. In the network, this is represented by a relatively thin red connection pointing from NYMEX to EUA. More influential are the strong negative net spillovers from the crude oil market, carbon market, and U.S. stock market toward the Chinese stock market, with their absolute values particularly large in the early sample period. For example, the negative values for BRVSZ–BRVEUA and BRVSZ–BRVSP500 once reached as high as -11.0 and -12.0. This maps onto the network diagram as thick solid connecting lines emanating from the three nodes—NYMEX, EUA, and SP500—and all pointing toward the blue node SZ. This visually reveals that the Chinese stock market serves as the primary convergence hub for downside risk, a finding entirely consistent with the conclusion from the net spillover index that SZ is a deep net receiver.

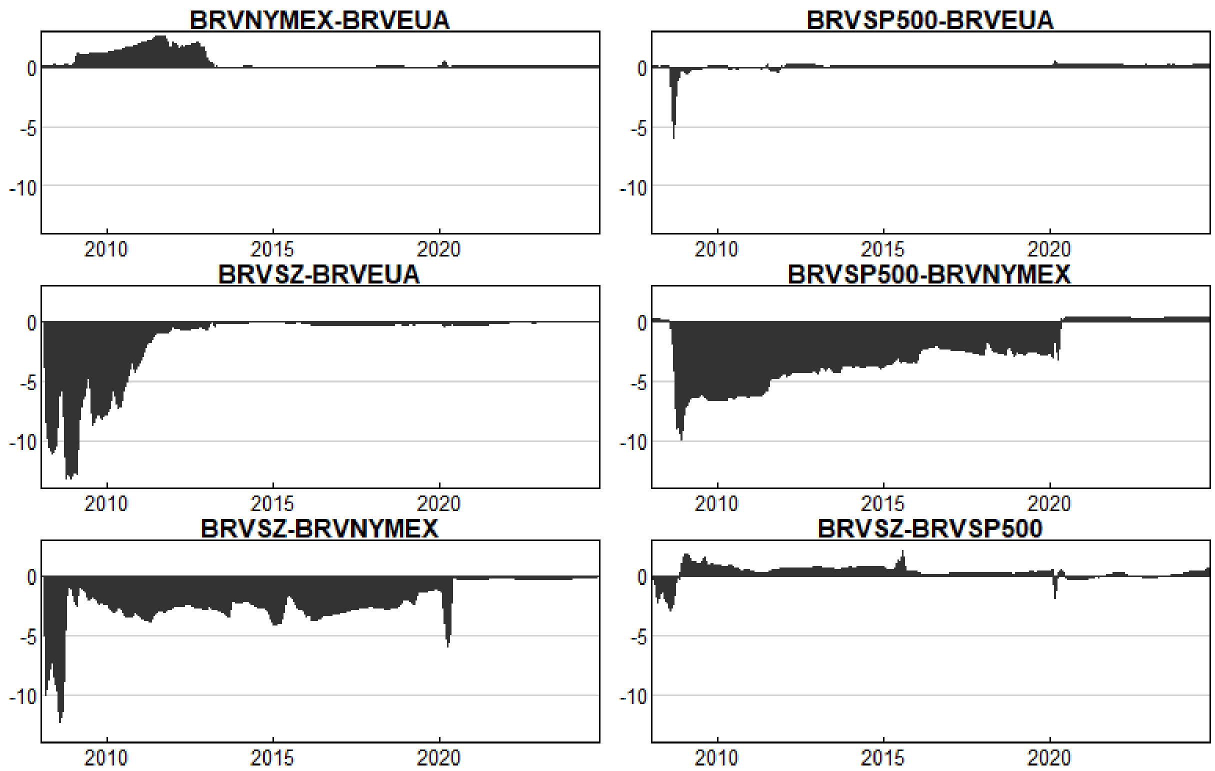

Fig. 17 BRV Pairwise Spillover

Considering the network diagram as a whole, the BRV network structure undergoes a dramatic evolution from "multi-source radiation" to "convergence and decay." In the early stage, the network was dominated by two major red nodes (NYMEX, EUA), which drove risk diffusion through thick output connections, especially those directed toward the blue node SZ. Over time, the output capacity of the red nodes diminished, and the spillover intensity of the entire network weakened systematically. The main connecting lines (including the line from SP500 to SZ) also became correspondingly thinner. By the end of the sample period, the network likely presented a sparse structure with very weak connections between nodes, making it difficult to distinguish dominant directions. This precisely corresponds to the macro-level phenomenon where the total BRV connectedness index plummeted to extremely low levels after 2020. This evolution profoundly reveals that the effectiveness of traditional transmission channels for downside risk—particularly from commodity markets to financial markets—underwent structural decay in the later part of the sample period.

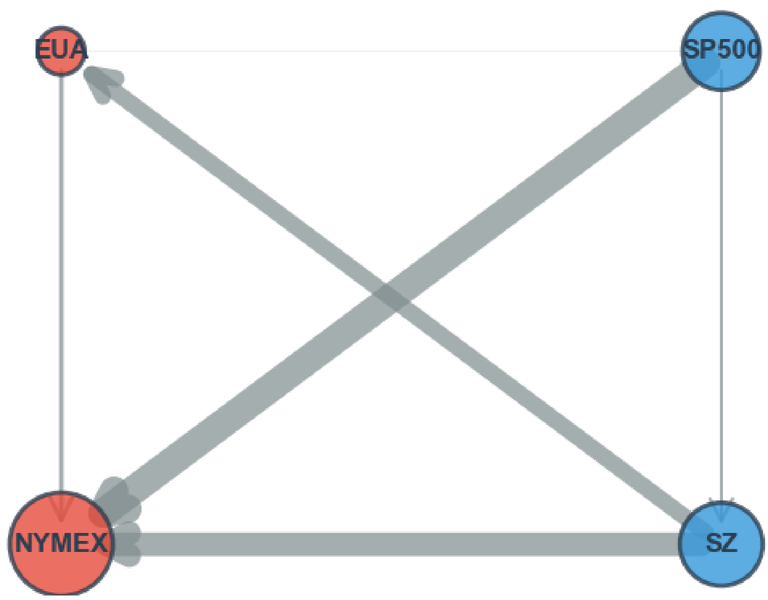

Fig. 18 BRV Spillover Network

5. Summary

This study systematically measures and compares the time-varying spillover networks across realized volatility (RV), good volatility (GRV), and bad volatility (BRV) dimensions by constructing a TVP-VAR-DY model that includes the carbon market (EUA), crude oil market (NYMEX), U.S. stock market (SP500), and Chinese stock market (SZ). The empirical results reveal that cross-market risk and sentiment transmission exhibit pronounced characteristics of dynamics, asymmetry, and structural evolution. The main conclusions are as follows:

First, the overall connectedness among markets is not constant but driven by major macroeconomic events. The total connectedness index experienced strong shocks during the 2008 financial crisis and the 2020 COVID-19 crisis for RV and BRV, whereas GRV peaked in 2021 during the period of heightened global consensus on green policies. This indicates that the contagion of "bad news" and "good news" is triggered by panic sentiment and clear policy narratives, respectively, reflecting fundamentally different driving mechanisms and cycles.

Second, the roles of key markets within the risk network demonstrate profound state dependence and asymmetry. The study finds that the role of U.S. stocks is multifaceted: in the RV dimension, they are a major volatility receiver; in the GRV dimension, they serve as the ultimate "convergence point" and net receiver of positive sentiment; and in the BRV dimension, they were significant risk receivers in the early period, though their influence diminished later. This finding challenges the traditional view of U.S. stocks as a singular "global risk transmitter," revealing their complex role as simultaneous "sentiment absorbers." In contrast, the Chinese stock market consistently acts as the most stable and prominent net risk receiver across all volatility states, particularly within the downside risk (BRV) network, highlighting its sustained vulnerability to global risk shocks. The carbon and crude oil markets were important sources of risk and sentiment in the early sample period, but their net spillover influence declined rapidly over time, eventually transforming into neutral transmission nodes within the network.

Finally, risk transmission pathways exhibit a clear hierarchical structure and directionality. There is a stable spillover from the crude oil market to the carbon market (especially in RV and BRV), forming an "energy-carbon price" transmission axis. More critically, risk transmission demonstrates a unidirectional net flow from the U.S. stock market to the Chinese stock market, constituting an internal channel connecting the two financial cores. The network structure evolved from an early "commodity-market-driven" pattern to a later "financial-core-receiving" pattern, with traditional channels for downside risk transmission showing signs of structural decay in effectiveness toward the end of the sample period.

Theoretical Contributions and Practical Implications: By integrating dynamic and asymmetric perspectives, this study provides a new empirical framework for understanding the complex linkages among traditional finance, energy commodities, and emerging environmental policy markets against the backdrop of energy transition and major-power dynamics. The conclusions offer important insights for policymakers and market participants: regulators need to focus on the asymmetric mechanisms of risk contagion, particularly by strengthening the monitoring of cross-border downside risk transmission and external shocks to the Chinese stock market during crises. Investors, on the other hand, should dynamically adjust asset allocations according to different macroeconomic scenarios (e.g., crises, policy-optimism periods) to respond to the time-varying nature of market roles. Future research could incorporate additional markets (such as bonds and foreign exchange) and more refined volatility decompositions to more comprehensively map the connectivity of global financial networks.

References

[1] Adekoya O B, Akinseye A B, Antonakakis N, et al. Crude oil and Islamic sectoral stocks: Asymmetric TVP-VAR connectedness and investment strategies [J]. Resources Policy, 2022, 78: 102877.

[2] Akhtaruzzaman M, Boubaker S, Sensoy A. Financial contagion during COVID–19 crisis [J]. Finance research letters, 2021, 38: 101604.

[3] Alharbey M, Alfahaid T M, Ben-Salha O. Asymmetric volatility spillover between oil prices and regional renewable energy stock markets: A time-varying parameter vector autoregressive-based connectedness approach [J]. AIMS Mathematics, 2023, 8 (12): 30639-30667.

[4] Ali F, Khurram M U. Leverage effects, volatility innovation spillovers, and inter-and intra-market asymmetric dependencies in cryptocurrencies and CFDs on equity indices: Evidence from high-frequency around-the-clock data [J]. International Review of Financial Analysis, 2025: 104636.

[5] Alomari M, Belghouthi H E, Mensi W, et al. Extreme time-frequency connectedness between energy sector markets and financial markets [J]. Economic Analysis and Policy, 2024, 84: 847-877.

[6] Andersen T G, Bollerslev T, Diebold F X, et al. Modeling and forecasting realized volatility [J]. Econometrica, 2003, 71 (2): 579-625.

[7] Andersen T G, Bollerslev T, Diebold F X, et al. The distribution of realized exchange rate volatility [J]. Journal of the American statistical association, 2001, 96 (453): 42-55.

[8] Antonakakis N, Chatziantoniou I, Gabauer D. Refined measures of dynamic connectedness based on time-varying parameter vector autoregressions [J]. Journal of Risk and Financial Management, 2020, 13 (4): 84.

[9] Arouri M E H, Lahiani A, Nguyen D K. Return and volatility transmission between world oil prices and stock markets of the GCC countries [J]. Economic Modelling, 2011, 28 (4): 1815-1825.

[10] Avramov D, Chordia T, Goyal A. The impact of trades on daily volatility [J]. The Review of Financial Studies, 2006, 19 (4): 1241-1277.

[11] Baker S R, Bloom N, Davis S J. Measuring economic policy uncertainty [J]. The quarterly journal of economics, 2016, 131 (4): 1593-1636.

[12] Barndorff-Nielsen O E, Kinnebrock S, Shephard N. Measuring downside risk-realised semivariance [J]. CREATES Research Paper, 2008 (2008-42).

[13] Barndorff-Nielsen O E, Shephard N. Econometric analysis of realized volatility and its use in estimating stochastic volatility models [J]. Journal of the Royal Statistical Society Series B: Statistical Methodology, 2002, 64 (2): 253-280.

[14] Barndorff-Nielsen O E, Shephard N. Power and bipower variation with stochastic volatility and jumps [J]. Journal of financial econometrics, 2004, 2 (1): 1-37.

[15] Baruník J, Kočenda E, Vácha L. Asymmetric volatility connectedness on the forex market [J]. Journal of International Money and Finance, 2017, 77: 39-56.

[16] Beckmann J, Czudaj R. Gold as an inflation hedge in a time-varying coefficient framework [J]. The North American Journal of Economics and Finance, 2013, 24: 208-222.

[17] Bekaert G, Wu G. Asymmetric volatility and risk in equity markets [J]. The review of financial studies, 2000, 13 (1): 1-42.

[18] BenSaïda A. Good and bad volatility spillovers: An asymmetric connectedness [J]. Journal of Financial Markets, 2019, 43: 78-95.

[19] Bloom N. The impact of uncertainty shocks [J]. econometrica, 2009, 77 (3): 623-685.

[20] Bollerslev T, Litvinova J, Tauchen G. Leverage and volatility feedback effects in high-frequency data [J]. Journal of Financial Econometrics, 2006, 4 (3): 353-384.

[21] Caldara D, Iacoviello M. Measuring geopolitical risk [J]. American economic review, 2022, 112 (4): 1194-1225.

[22] Chatziantoniou I, Gabauer D, Gupta R. Integration and risk transmission in the market for crude oil: New evidence from a time-varying parameter frequency connectedness approach [J]. Resources Policy, 2023, 84: 103729.

[23] Chen X, Ghysels E. News—good or bad—and its impact on volatility predictions over multiple horizons [J]. The Review of Financial Studies, 2011, 24 (1): 46-81.

[24] Chen X, Yao Y, Wang L, et al. How EPU, VIX, and GPR interact with the dynamic connectedness among commodity and financial markets: Evidence from wavelet analysis [J]. The North American Journal of Economics and Finance, 2024, 74: 102217.

[25] Chevallier J. Macroeconomics, finance, commodities: Interactions with carbon markets in a data-rich model [J]. Economic modelling, 2011, 28 (1-2): 557-567.

[26] Corsi F. A simple approximate long-memory model of realized volatility [J]. Journal of financial econometrics, 2009, 7 (2): 174-196.

[27] Diebold F X, Yilmaz K. Better to give than to receive: Predictive directional measurement of volatility spillovers [J]. International Journal of forecasting, 2012, 28 (1): 57-66.

[28] Diebold F X, Yilmaz K. Measuring financial asset return and volatility spillovers, with application to global equity markets [J]. The Economic Journal, 2009, 119 (534): 158-171.

[29] Diebold F X, Yılmaz K. On the network topology of variance decompositions: Measuring the connectedness of financial firms [J]. Journal of econometrics, 2014, 182 (1): 119-134.

[30] Ehrmann M, Fratzscher M, Rigobon R. Stocks, bonds, money markets and exchange rates: measuring international financial transmission [J]. Journal of Applied Econometrics, 2011, 26 (6): 948-974.

[31] Forbes K J, Rigobon R. No contagion, only interdependence: measuring stock market comovements [J]. The journal of Finance, 2002, 57 (5): 2223-2261.

[32] Forbes K J, Warnock F E. Capital flow waves—or ripples? Extreme capital flow movements since the crisis [J]. Journal of International Money and Finance, 2021, 116: 102394.

[33] Gavriilidis K. Measuring climate policy uncertainty [J]. Available at SSRN 3847388, 2021.