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Quantile and Frequency Connectedness Between Cryptocurrencies, Tokenized Gold, and Energy Assets: Evidence from a Multi-Layer Spillover Framework

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Abstract

This paper investigates the dynamic spillover structure among heterogeneous asset classes, Bitcoin, gold, tokenized gold (DGX and PAXG), and energy commodities (WTI and gas), using a unified quantile and frequency-domain connectedness framework. Based on daily data from November 1, 2023, to March 31, 2025, our analysis captures nonlinear, regime-dependent, and time-frequency-specific transmission channels that conventional models often overlook. The results reveal that systemic connectedness intensifies sharply during tail market events, with gold and PAXG consistently emerging as dominant net transmitters of shocks, particularly under bullish regimes. In contrast, WTI, gas, and Bitcoin generally act as net receivers, with their exposure highly contingent on market conditions. Frequency decomposition shows that short-term spillovers overwhelmingly dominate system-wide risk transmission, although long-term dependencies strengthen during periods of elevated uncertainty—most notably in early 2025 amid trade policy tensions. These findings highlight the importance of high-frequency monitoring, regime-aware diversification, and the evolving systemic role of tokenized commodities in modern financial networks.

Keywords: *Connectedness, spillover, Bitcoin, gold, gold-backed cryptocurrencies, COVID-19, Russia-Ukraine war.*

Introduction

The COVID-19 pandemic, first recognized in Wuhan, China, in December 2019, has endured for more than two years, negatively affecting nearly every sector worldwide, including energy markets. Specifically, this public health emergency has led to a drop in global energy commodity prices (Albulescu, 2020; Bakas and Triantafyllou, 2020; Mokni et al., 2021; Umar et al., 2021; Iqbal et al., 2023).

The oil markets experienced the most significant disruptions, primarily due to reduced travel caused by mitigation measures (Ahmed et al., 2021). For example, by the end of March 2020, Brent crude oil prices fell to approximately \$23 per barrel, marking the lowest point since November 2002 (Dutta et al., 2020). Similarly, the price of US West Texas Intermediate (WTI) dropped below \$20 per barrel, reaching its lowest level in 18 years (Dutta et al., 2020). According to Corbet et al. (2020a), the WTI crude oil price continued to decline on April 20, 2020. Gil-Alana and Monge (2020) observed that the crude oil market became inefficient during the COVID-19 crisis. Devpura and Narayan

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(2020) highlighted a surge in oil price volatility after the pandemic began. Huang and Zheng (2020) noted that the sharp decline in crude oil demand during the outbreak led to negative prices for WTI crude oil. Similarly, Zhang and Hamori (2021) found that the effects of COVID-19 led to an unprecedented level of risk, causing a dramatic drop in oil prices.

The COVID-19 pandemic has significantly impacted natural gas prices, leading to fluctuations and changes in the market. The pandemic's onset resulted in a sharp decline in natural gas demand due to reduced economic activity and travel restrictions (Cieślik et al., 2022). Kumar et al. (2022) identified a global shock in the gas market during the health crisis, driven by a decrease in both demand and supply. Norouzi (2021) highlighted that the oil and gas sectors were notably affected by the consequences of COVID-19. Additionally, Iyke (2020) noted that the pandemic accounted for 27% of the return volatility in the gas and oil markets.

Amid the ongoing COVID-19 pandemic, the world experienced another major black swan event: the Russian-Ukrainian military conflict, which began on February 24, 2022. This event has led to widespread consequences, creating significant global uncertainty (Berninger et al., 2022; Bossman et al., 2022; Boungou and Yatié, 2022; Boubaker et al., 2022; Karkowska and Urjasz, 2023). The conflict has become a major topic of discussion, deeply affecting the global economy, particularly the international crude oil and gas markets (Chen et al., 2023). These energy markets have experienced considerable disruption, with noticeable changes in both supply and pricing (Liadze et al., 2022). For example, the prices of Brent and West Texas Intermediate (WTI) crude oil surpassed 100 US dollars per barrel on the day of the invasion. Additionally, oil transitioned from being a net receiver to a net producer of spillovers during the crisis (Adekoya et al., 2022). Similarly, gas prices surged, reaching around 4 US dollars per gallon (Liadze et al., 2022).

Chishti et al. (2023) found that the Russia-Ukraine conflict significantly intensified market conditions in both the crude and Brent oil markets across various quantiles. Wang et al. (2022) observed a shift in the roles of commodities within return and volatility regimes, with their findings showing that crude oil has become a net producer of volatility spillovers. Fang and Shao (2022) explored how the Russia-Ukraine conflict heightened market instability in commodity markets, revealing a notable increase in volatility within energy markets after the conflict escalated. Saad (2023) utilized an event study methodology alongside GARCH models to analyze the impact of the conflict on returns and volatility in the U.S. natural gas futures market. This study revealed that natural gas futures prices reacted negatively to the war.

The price volatility in oil and gas markets during the COVID-19 pandemic and the Russia-Ukraine conflict has heightened the potential for tail risks in these assets. This indicates that investing in these markets has become riskier, with the possibility of more significant losses. As a result, identifying alternative investment options to reduce the risks tied to oil and gas is essential.

While most asset classes saw a significant increase in correlations, gold was the only asset to experience a rise in value in 2020. Several studies have investigated whether gold acts as a safe-haven asset during times of market turmoil (Baur and Lucey, 2010; Baur and McDermott, 2010; Reboredo, 2013; Ciner et al., 2013; Shahzad et al., 2020; Adekoya et al., 2021). Throughout history, gold has been regarded both as a means of diversification and a hedge during periods of economic stability, as well as a safe haven in times of crisis and market instability (Baur and Lucey, 2010; Baur and McDermott, 2010). Another area of recent research has focused on assessing Bitcoin's safe-haven qualities. Bitcoin is recognized as an asset for diversification, hedging, and risk management (Bouri et al., 2017; Bouri et al., 2020; Frikha et al., 2023). However, its effectiveness as a safe haven is often limited due to its price volatility (Jeribi and Snene_Manzli, 2020; Cheema et al., 2020; Fakhfekh and Jeribi, 2020; Corbet et al., 2020a; Jeribi and Masmoudi, 2021).

Furthermore, considerable attention has been given to examining the potential of alternative forms of cryptocurrencies, particularly stablecoins, in relation to conventional assets. These digital currencies are typically backed by relatively stable assets, such as the U.S. dollar or precious metals. Initially created to provide a more adaptable substitute for fiat currencies within cryptocurrency exchanges, stablecoins are increasingly playing a significant role in both the cryptocurrency ecosystem and the broader sphere of alternative finance.

Gold-backed cryptocurrencies represent a prominent category of stablecoins, functioning as digital assets whose value is tied to physical gold. As a subset of cryptocurrencies, they are intended to counter the high volatility typically associated with conventional digital currencies. According to Mita et al. (2019) and Sidorenko (2020), these stablecoins are developed to stabilize market price fluctuations. Meanwhile, Wei (2018), Wang et al. (2020), and Baur and Hoang (2020) regard stablecoins as reliable financial instruments that can offer protection in times of economic or financial distress.

In this paper, we conduct an empirical investigation of the connectedness and spillover relationships between Bitcoin, gold, gold-backed cryptocurrencies and energy commodities (crude oil and natural gas) amid the recent COVID-19 pandemic and the ongoing Russia-Ukraine war. The examination of the connectedness among these assets is conducted using the quantile connectedness approach proposed by Ando et al. (2022), Bouri et al. (2021), and Chatziantoniou et al. (2021), based on the connectedness approach of Diebold and Yilmaz (2012, 2014). Our findings reveal diverse influence dynamics among assets, with gold and PAXG consistently emerging as dominant net transmitters of shocks, particularly under bullish regimes. In contrast, WTI, gas, and Bitcoin generally act as net receivers, with their exposure highly contingent on market conditions. Frequency decomposition shows that short-term spillovers overwhelmingly dominate system-wide risk transmission, although long-term dependencies strengthen during periods of elevated uncertainty, most notably in early 2025 amid trade policy tensions. These findings highlight the importance of high-frequency monitoring, regime-aware diversification, and the evolving systemic role of tokenized commodities in modern financial networks.

To the best of our understanding, this study is among the first to analyze the outlined relationships within the context of the ongoing pandemic and geopolitical conflict. Since economic recessions, terrorist threats, pandemics, and wars often serve as critical factors in portfolio risk evaluation, our results may hold significant value for investors engaged in both commodity and digital asset markets. Unlike previous research that primarily explored the interlinkages between Bitcoin, gold, and energy commodities, this work extends the scope by assessing the role of gold-backed cryptocurrencies. This inclusion enriches the analysis by capturing unique attributes of digital gold assets, thereby addressing a gap in the literature. Moreover, the use of a novel Quantile-VAR approach across the median and other quantiles allows for a more detailed and refined assessment than traditional models typically provide.

The findings of this study offer practical value for both policymakers and investors operating in volatile economic environments. They deliver important guidance for developing robust risk management approaches and making well-informed investment choices during times of crisis.

The structure of the paper is organized as follows: Section 2 reviews the existing literature, Section 3 outlines the data and methodological approach, Section 4 analyzes the empirical findings, and Section 5 offers concluding remarks.

Literature Review

The recent crises have heightened the risks associated with commodity markets, increasing the potential for substantial losses. As a result, commodity investors should consider adjusting their capital allocation strategies by incorporating assets that offer diversification, hedging, and safe-haven benefits into their commodity-focused portfolios.

According to the definitions proposed by Baur and Lucey (2010) and Baur and McDermott (2010), an asset qualifies as a diversifier when it maintains a positive correlation with other assets. It is classified as a hedge when it exhibits no correlation or a negative correlation with other assets under normal market conditions. Conversely, an asset is identified as a safe haven if it remains uncorrelated or negatively correlated with other assets specifically during times of financial distress or market turbulence.

Gold, traditionally a store of value and safe-haven asset, maintains a well-established relationship with energy commodities. Energy shocks, particularly those involving oil prices, often lead to increased demand for gold as a hedge against inflation and geopolitical risk. During turbulent times, gold has shown a consistent ability to reduce portfolio risk associated with energy price volatility (Snene Manzli and Jeribi, 2024; Chang et al., 2024).

Unlike Bitcoin, gold's correlation with energy markets tends to be more stable and defensive in nature. For instance, when crude oil prices spike due to supply shocks or conflicts, investors often reallocate their funds to gold to protect against currency depreciation and inflation. This behavior has reinforced gold's role as a hedge, especially during periods of systemic instability, such as the COVID-19 pandemic and the Russia-Ukraine war (Chang et al., 2024)

For instance, Baur and Lucey (2010) and Baur and McDermott (2010) evaluate gold's effectiveness in protecting against downturns in U.S. and European stock markets, concluding that it functions as both a hedge and a safe haven during major market disruptions. Similar conclusions are drawn by Reboredo (2013) and Ciner et al. (2013). Triki and Ben Maatoug (2021) highlight gold's suitability as both a diversifier and a safe haven under extreme financial stress. Additionally, Shahzad et al. (2020) examine gold's capacity to diversify, hedge, and offer refuge, confirming its strong performance in turbulent conditions.

Employing the NARDL framework, Ghorbel et al. (2022) demonstrated that gold functions effectively as a long-term hedge or safe haven. Adekoya et al. (2021) also observed that gold acts as a reliable hedge against crude oil market risks during the COVID-19 crisis. Similarly, Dutta et al. (2020) confirmed gold's resilience as a safe haven for crude oil markets throughout the pandemic. Shakil et al. (2018) highlighted gold's role as an optimal safe haven for commodities, emphasizing its risk-reducing impact when included in investment portfolios during periods of financial instability. Oosterlinck et al. (2022), utilizing the DCC model to analyze periods before and during the Russia-Ukraine conflict in 2022, concluded that gold serves as an effective diversifier amid geopolitical tensions. In addition, Naeem et al. (2022) explored gold's safe haven and hedging attributes in relation to industrial metals and agricultural commodities, both before and after the Global Financial Crisis (GFC), and found low correlations, reinforcing gold's function as a refuge during financial turmoil.

Wang et al. (2023) highlighted that gold effectively acts as a safe-haven asset for the crude oil market in both pre-pandemic and pandemic periods. Similarly, Cui et al. (2023) identified gold as an optimal safe haven for oil during the COVID-19 crisis. In their study, Ari et al. (2023) examined the effects of gold price fluctuations on the energy sector amid the COVID-19 outbreak and the Russia-Ukraine conflict. Their analysis revealed that variations in gold returns did not influence energy sector returns, reinforcing gold's role as a reliable safe haven.

In addition to gold, cryptocurrencies, particularly Bitcoin, have gained recognition as effective hedging and safe-haven assets, attracting significant interest from investors. Bitcoin's link to energy markets stems not only from its role as a speculative digital asset but also from its mining process, which consumes large amounts of electricity. Bitcoin's reliance on Proof-of-Work (PoW) consensus mechanisms has drawn criticism due to its substantial environmental footprint. Despite representing only 0.06% of total cashless transactions, Bitcoin accounts for a disproportionately high 0.3% of global electricity consumption (Manahov and Li, 2025).

This energy dependency creates both financial and environmental interconnectedness. For example, fluctuations in electricity prices, driven by oil and natural gas markets, can directly influence Bitcoin mining profitability and activity. Additionally, geopolitical shocks such as the Russia-Ukraine conflict and the COVID-19 pandemic have increased the volatility and spillovers between Bitcoin and energy markets, particularly during periods of heightened uncertainty (Kantaphayao, W., & Sukcharoensin, 2021; Huyen et al., 2023; Snene Manzli and Jeribi, 2024). Research shows that external shocks often trigger strong and unidirectional volatility transmissions from energy markets to Bitcoin markets, but not always the other way around (Huyen et al., 2023).

Moreover, Extensive research has explored the hedging and safe-haven properties of cryptocurrencies. For example, Bouri et al. (2019) analyzed the diversification and hedging capabilities of Bitcoin and other cryptocurrencies in relation to financial equities, finding that these digital assets serve as strong hedging tools. Guesmi et al. (2019), using various multivariate GARCH models, confirmed that Bitcoin can be utilized to mitigate risks associated with investments in diverse financial assets. Corbet et al. (2020b) examined how investor sentiment regarding the COVID-19 pandemic influenced cryptocurrency performance, highlighting that digital assets offer diversification benefits and act as safe havens, similar to gold, during past crises. Additionally, Hai Le et al. (2021) emphasized Bitcoin's role as a safe haven during the COVID-19 crisis.

Tut (2022) argues that Bitcoin, by enabling large sums of money to be transferred across borders, could enhance financial security during times of military conflict. Bouri et al. (2017) propose that Bitcoin serves as a strong hedge and a reliable safe haven against fluctuations in commodity markets. According to Selmi et al. (2018), both Bitcoin and gold can function as assets for diversification, hedging, and providing security in response to changes in oil prices. Naeem et al. (2020) highlight the crucial role cryptocurrencies play as hedging and safe-haven assets for commodities. Hoang et al. (2020) suggest that Bitcoin has the potential to act as a safe haven against commodity market fluctuations. Ma (2022) states that Bitcoin is a valuable hedging instrument against the disruptive effects of the global crude oil market and the price surges caused by the Russia-Ukraine conflict.

In addition to well-known cryptocurrencies like Bitcoin, there has been increasing interest in examining the potential of alternative crypto assets, such as gold-backed stablecoins. These assets are digital representations of physical gold on blockchain platforms that combines the safe-haven properties of gold with the transactional benefits of cryptocurrencies. Stablecoins such as PAX Gold and Digix Gold allow fractional ownership, 24/7 trading, and blockchain-verified custody, increasing their appeal to investors seeking both security and liquidity (Snene Manzli and Jeribi, 2024).

The integration of gold-backed cryptocurrencies into energy markets is particularly notable during energy-related crises. These assets has proven effective as a hedge against extreme volatility in energy commodities, including oil and natural gas. Empirical studies by Snene Manzli and Jeribi (2024) have shown that during periods of energy price uncertainty, gold-backed crypto assets reduce portfolio risk more efficiently than Bitcoin and sometimes even traditional gold.

Moreover, Baur and Hoang (2020) explore the safe haven role of stablecoins in relation to Bitcoin price volatility, finding that stablecoins serve as effective safe havens. Xie et al. (2021) examine the safe haven potential of stablecoins for traditional cryptocurrencies during the COVID-19 pandemic, confirming their safe haven characteristics both before and during the crisis. Ncir et al. (2021) show that gold-backed cryptocurrencies offered lower risk compared to Bitcoin during the COVID-19 crisis. Yousaf and Yarovaya (2022) argue that investing in gold-backed cryptocurrencies reduces portfolio risk in the equity sector during the COVID-19 pandemic. Additionally, Syuhada et al. (2022) find that adding stablecoins to a portfolio of oil and Bitcoin significantly lowers overall risk during the COVID-19 period. Hampel et al. (2022) investigate the safe haven potential of both traditional cryptocurrencies and stablecoins for financial markets during the Russia-Ukraine conflict, revealing that stablecoins can act as safe havens for gold and stock markets during this geopolitical crisis.

The interconnectedness between Bitcoin, gold, gold-backed cryptocurrencies, and energy markets reflects a complex and evolving financial ecosystem. While gold remains a consistent hedge against energy volatility, Bitcoin’s relationship with energy markets is shaped by its high electricity demands and crisis-specific market reactions. Gold-backed cryptocurrencies stands out as a promising digital asset that bridges the strengths of traditional gold with the efficiency of blockchain, especially in managing energy-related risks.

These dynamics have significant implications for investors, policymakers, and environmental sustainability. Understanding the nuanced linkages among these assets is crucial for designing effective investment strategies and regulatory frameworks that support innovation while addressing energy consumption and systemic risks.

Data and methodology

1.1. Data:

The paper examines the connectedness and spillover relationships between four categories of assets, namely conventional cryptocurrency (Bitcoin), financial assets (gold), gold-backed currencies (PAXG and DGX), and energy assets, namely oil (WTI) and gas (Natural Gas Futures NGK2). The data span from November 1st, 2023, to March 31, 2025. The timeframe is marked by major events such as the global COVID-19 pandemic and the war between Ukraine and Russia. These events had a substantial impact on financial markets, allowing us to examine not just the dynamic connectedness within the digital (respectively, financial) market and energy market but also the extent to which these assets are subject to instabilities caused by broader market shifts. The returns of the different variables are calculated by employing the formula $R_t = \ln(P_t/P_{t-1})$, with P_t denoting the price for the current day.

1.2.Methodology:

To analyze the quantile spillover mechanism across various digital and financial markets, we employ the quantile connectedness approach proposed by Ando et al. (2022), Bouri et al. (2021), and Chatziantoniou et al. (2021), based on the connectedness approach of Diebold and Yilmaz (2012, 2014). We begin by computing the overall connectedness measures using a quantile vector autoregression (QVAR(p)). The model can be presented as follows:

$$x_t = \mu_t(\tau) + \Phi_1(\tau)x_{t-1} + \Phi_2(\tau)x_{t-2} + \cdots + \Phi_p(\tau)x_{t-p}\mu_t(\tau) \quad (1)$$

Where x_t and x_{t-j} are vectors representing endogenous variables with dimensions $N \times 1$. The parameter τ is a closed interval, which lies within the range [0, 1], while p represents the lag length of the QVAR model. (τ) is a $N\times1$ dimensional vector that represents the conditional mean, Φ_j (τ) is a $N \times N$ dimensional matrix of QVAR coefficients, and $\mu(\tau)$ is a $N \times 1$ dimensional error vector with an $N\times N$ dimensional error variance–covariance matrix, (τ).

Then, we apply the forward M-step Generalized Forecast Error Variance Decomposition (GFEVD), since the first equation needs to be transformed into the QVMA(∞) form by applying Wold's theorem. The QVMA(∞) can be obtained from the following equation :

$$x_t = \mu(\tau) + \sum_{j=1}^{p} \Phi_j(\tau)x_{t-j} + u_t(\tau) = \mu(\tau) + \sum_{i=0}^{\infty} \Psi_i(\tau)u_{t-i} \quad (2)$$

Next, we calculate the generalized forecast error variance decomposition (GFEVD) with a forecast horizon of H. This is a central step in the connectedness approach (Koop et al., 1996; Pesaran and Shin, 1998) as follow:

$$\theta_{ij}^{g}(H) = \frac{(\Sigma(\tau)_{jj}^{-1}\sum_{h=0}^{H}((\Psi h(\tau)\Sigma(\tau))ij)2}{\sum_{h=0}^{H}(\Psi h(\tau)\Sigma(\tau)\Psi\prime h(\tau))ii} \quad (3)$$

$$\tilde{\theta}_{ij}(H) = \theta_{ij}(H)\sum_{k=1}^{N}\theta_{ij}(H), \text{ with } \sum_{i=1}^{N}\tilde{\theta}_{ij}(H) = 1 \text{ and } \sum_{j=1}^{N}\tilde{\theta}_{ij}(H) = N \quad (4)$$

Table 1. Connectedness table based on the FEVD approach

	y_1	y_2	..	y_K	*From*
y_1	$C^H_{1\leftarrow 1}$	$C^H_{1\leftarrow 2}$	..	$C^H_{1\leftarrow K}$	$F_{1\leftarrow j} = \sum_{j=1}^{K} C^H_{1\leftarrow j}, j \neq 1$
y_2	$C^H_{2\leftarrow 1}$	$C^H_{2\leftarrow 2}$	..	$C^H_{2\leftarrow K}$	$F_{2\leftarrow j} = \sum_{j=1}^{K} C^H_{2\leftarrow j}, j \neq 2$
:	:	:		:	:
y_K	$C^H_{K\leftarrow 1}$	$C^H_{K\leftarrow 2}$	..	$C^H_{K\leftarrow K}$	$F_{K\leftarrow j} = \sum_{j=1}^{K} C^H_{K\leftarrow j}, j \neq K$
To	$T_{i\leftarrow 1} = \sum_{i=1}^{K} C^H_{i\leftarrow 1}$ $i \neq 1$	$T_{i\leftarrow 2} = \sum_{i=1}^{K} C^H_{i\leftarrow 2}$ $i \neq 2$	..	$T_{i\leftarrow K} = \sum_{i=1}^{K} C^H_{i\leftarrow K}$ $i \neq K$	$\frac{1}{K}\sum_{i,j=1}^{K} C^H_{i\leftarrow j}$ $i \neq j$
Net	$T_{i\leftarrow 1} - F_{1\leftarrow j}$	$T_{i\leftarrow 2} - F_{2\leftarrow j}$	..	$T_{i\leftarrow K} - F_{K\leftarrow j}$	

Note: following Diebold and Yilmaz (2009, 2014) and Zhang (2017), H is set to be 10 days.

Following Diebold and Yilmaz (2012) approach, the GFEVD based spillover measures are defined as follows:

The total directional connectedness with respect to others assesses how much an impact in series i influences all other series j.

$$TO_i(H) = \sum_{i=1, i\neq j}^{N} \tilde{\theta}_{ji}\,(H) \quad (5)$$

The total directional connectedness originating from others quantifies the level of impact on series i caused by shocks in all other series j.

$$FROM_i(H) = \sum_{i=1, i\neq j}^{N} \tilde{\theta}_{ij}\,(H) \quad (6)$$

The overall net total directional connectedness captures the difference between the total directional connectedness towards others and the total directional connectedness from others. This disparity can be interpreted as the net impact of series i on the predefined network.

$$NET_i(H) \;=\; TO_i(H) - FROM_i(H) \quad (7)$$

The computation of the overall total connectedness index (TCI), which evaluates the degree of interconnectedness within the network. A higher value of TCI signifies increased market risk, while a lower value indicates the opposite (Chatziantoniou et al., 2021).

$$TCI(H) = N - 1 \sum_{i=1}^{N} TO_i(H) = N - 1 \sum_{i=1}^{N} FROM_i(H) \qquad (8)$$

Using Stiassny's (1996) spectral decomposition method, we intend to analyze the link between connectedness and frequency. Firstly, we inspect the frequency response function, represented as $(e^{-iw}) = \sum_{h=0}^{\infty} e^{-iw} h\, \Psi h$, where $i = \sqrt{-1}$ and ω is the frequency.

$$S_x(w) = \sum_{h=-\infty}^{\infty} E(x_t x_t - h')e^{-iw}h = \left(e^{-iw}h\right)_t \Psi'(e^{+iw}h) \quad (9)$$

Similarly, the frequency-based Generalized Forecast Error Variance Decomposition (GFEVD) is a fusion of the spectral density and the GFEVD. In fact, normalizing the frequency GFEVD is key, and is presented as follows:

$$\theta_{ij}\,(H) \;=\; \frac{(\Sigma(\tau)_{jj}^{-1} \sum_{h=0}^{\infty}((\Psi(\tau)e^{-iw}h\Sigma(\tau))ij\,)2}{\sum_{h=0}^{H}(\Psi e^{-iw}h)\Sigma(\tau)\Psi(\tau)(e^{iw}h)ii} \quad (10)$$

$$\tilde{\theta}_{ij}\,(w) = \theta_{ij}\,(w) \sum_{k=1}^{N} \theta_{ij}\,(w) \quad (11)$$

The term $\tilde{\theta}ij\;(\omega)$ signifies the proportion of the spectrum of the i^{th} series at a given frequency ω that can be attributed to a shock in the j^{th} series. This measure is devoted to as a within-frequency sign, as it aids in assessing the interconnectedness between the two series at that particular frequency. To assess connectedness through both short-term and long-term time frames, instead of focusing on a single frequency, we aggregate all frequencies within a stated range, denoted as: d= (a, b): a, bÎ ($-\pi$, π), a<b:

$$\tilde{\theta}_{ij}(d) = \int_b^a \tilde{\theta}_{ij}(w)dw \ (12)$$

Consequently, we have the ability to compute similar connectedness measures as those introduced by Diebold and Yılmaz (2012, 2014). Nevertheless, in this case, these measures are recognized as frequency connectedness measures. They allow us to assess the transmission of effects within specific frequency ranges (represented by d), which can be interpreted in a comparable manner:

$$TO_i(d) = \sum_{i=1,i\neq j}^{N} \tilde{\theta}_{ji}\ (d) \ (13)$$

$$FROM_i(d) = \sum_{i=1,i\neq j}^{N} \tilde{\theta}_{ij}\ (d) \ (14)$$

$$NET_i(d) = \ TO_i(d) - FROM_i(d) \ (15)$$

$$TCI(d) = N - 1 \sum_{i=1}^{N} TO_i(d) = N - 1 \sum_{i=1}^{N} FROM_i(H) \ (16)$$

Here, we consider two frequency bands that capture short-term and long-term dynamics. The first band, $d1$ = (π⁄5, π), covers a range of 1 to 5 days, while the second band, $d2$ = (0, π⁄5], encompasses timeframes from 6 days to an infinite horizon. Therefore, $TO(d1)$, $FROMi(d1)$, $NETi(d1)$, and $TCI(d1)$ represent short-term total directional connectedness towards others, short-term total directional connectedness from others, short-term net total directional connectedness, and short-term total connectedness index, respectively. Alternatively, $TO(d2)$, $FROMi(d2)$, $NETi(d2)$, and $TCI(d2)$ depict long-term total directional connectedness towards others, long-term total directional connectedness from others, long-term net total directional connectedness, and long-term total connectedness index, respectively.

Empirical Results

1.3.Descriptive Statistics

This study presents a comprehensive analysis of the distributional properties and dependence structure of six financial assets: Bitcoin, gold, WTI, gas, DGX, and PAXG. The results indicate that all assets exhibit negligible mean returns and significant non-normality, as evidenced by notable skewness, excess kurtosis, and high Jarque–Bera statistics. Bitcoin, WTI, and DGX display pronounced asymmetries and fat-tailed behavior, highlighting their vulnerability to extreme market events. In contrast, gold and PAXG show lower volatility and relatively symmetric distributions, consistent with their roles as safe-haven assets.

Stationarity is confirmed across all return series using ERS tests, validating their suitability for time-series modeling. The Kendall rank correlation analysis reveals weak to moderate dependence among the assets, with the highest correlation observed between gold and PAXG, reflecting their shared underlying commodity. Gas stands out as largely uncorrelated with the other assets, suggesting its potential value for diversification. Overall, these findings underscore the heterogeneous statistical characteristics of traditional, energy, and digital assets, and support the need for risk models that account for nonlinear dependencies and higher-order moments.

Table 2. Descriptive statistics

	Bitcoin	Gold	WTI	Gas	DGX	PAXG
Mean	0.001	0.000	0.000	0.000	0.000	0.000
	(0.297)	(0.379)	(0.781)	(0.785)	(0.982)	(0.500)
Variance	0.002***	0.000***	0.002***	0.002***	0.012***	0.000***
Skewness	-1.686***	-0.427***	-3.159***	-0.118	2.400***	0.015
	(0.000)	(0.000)	(0.000)	(0.116)	(0.000)	(0.838)
Ex.Kurtosis	20.345***	3.431***	61.500***	1.410***	120.835***	5.552***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
JB	18783.310***	552.046***	168810.680***	90.287***	645901.922***	1361.700***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ERS	-11.930***	-7.782***	-11.594***	-13.093***	-16.859***	-7.873***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
kendall	Bitcoin	Gold	WTI	Gas	DGX	PAXG
Bitcoin	1.000***	0.081***	0.050**	0.014	0.223***	0.103***
Gold	0.081***	1.000***	0.094***	0.003	0.065***	0.582***
WTI	0.050**	0.094***	1.000***	0.074***	0.030	0.098***
Gas	0.014	0.003	0.074***	1.000***	-0.004	-0.005
DGX	0.223***	0.065***	0.030	-0.004	1.000***	0.085***
PAXG	0.103***	**0.582*****	0.098***	-0.005	0.085***	1.000***

1.4. Total Dynamic Connectedness

The TCI in Figure 1 exhibits a relatively moderate pattern for most of the observed period, fluctuating mainly between 30% and 45%, indicating a normal level of interconnectedness among the considered assets. However, beginning in early 2025, the TCI experiences a series of sharp spikes, peaking above 55%, signaling a period of exceptionally high systemic risk and contagion effects.

This period of heightened connectedness coincides with major geopolitical and economic events in March 2025. Notably, the announcement of aggressive U.S. trade tariffs, including a 10% general tariff on imports and specific surcharges on Chinese (54%) and EU (20%) goods, triggered widespread concerns about global trade disruptions. These developments, coupled with market turmoil in emerging economies such as Indonesia and sharp losses in U.S. equity indices, contributed to elevated investor uncertainty and synchronized reactions across asset classes.

The surge in the TCI during this window reflects the collapse of diversification benefits and the increased transmission of shocks across financial markets. In contrast, earlier phases, particularly in late 2023 and much of 2024, show more contained levels of connectedness, suggesting relatively decoupled asset behaviors and stable systemic conditions. The spike in the Total Connectedness Index in early 2025 underscores the system-wide implications of geopolitical shocks and policy uncertainty. For investors and policymakers, this highlights the importance of dynamic risk-monitoring frameworks capable of capturing abrupt shifts in market interdependencies, and reinforces the need for robust hedging strategies during periods of elevated global risk.

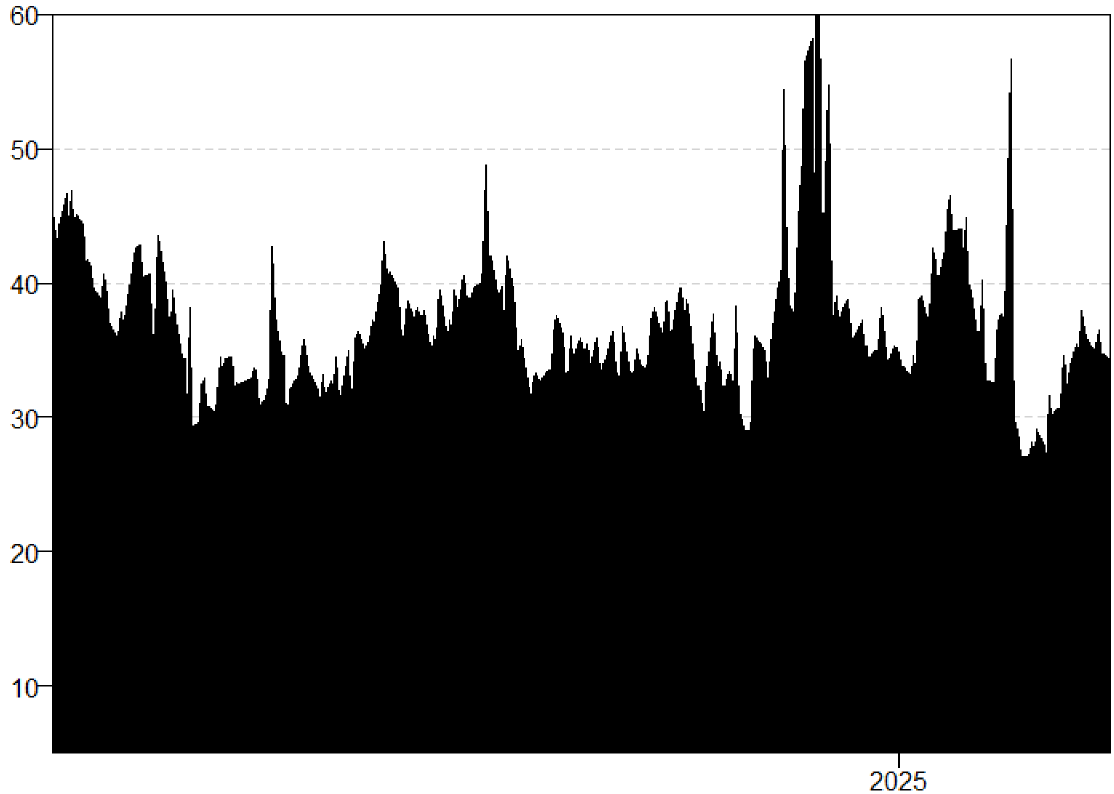


Figure 1: Total connectedness

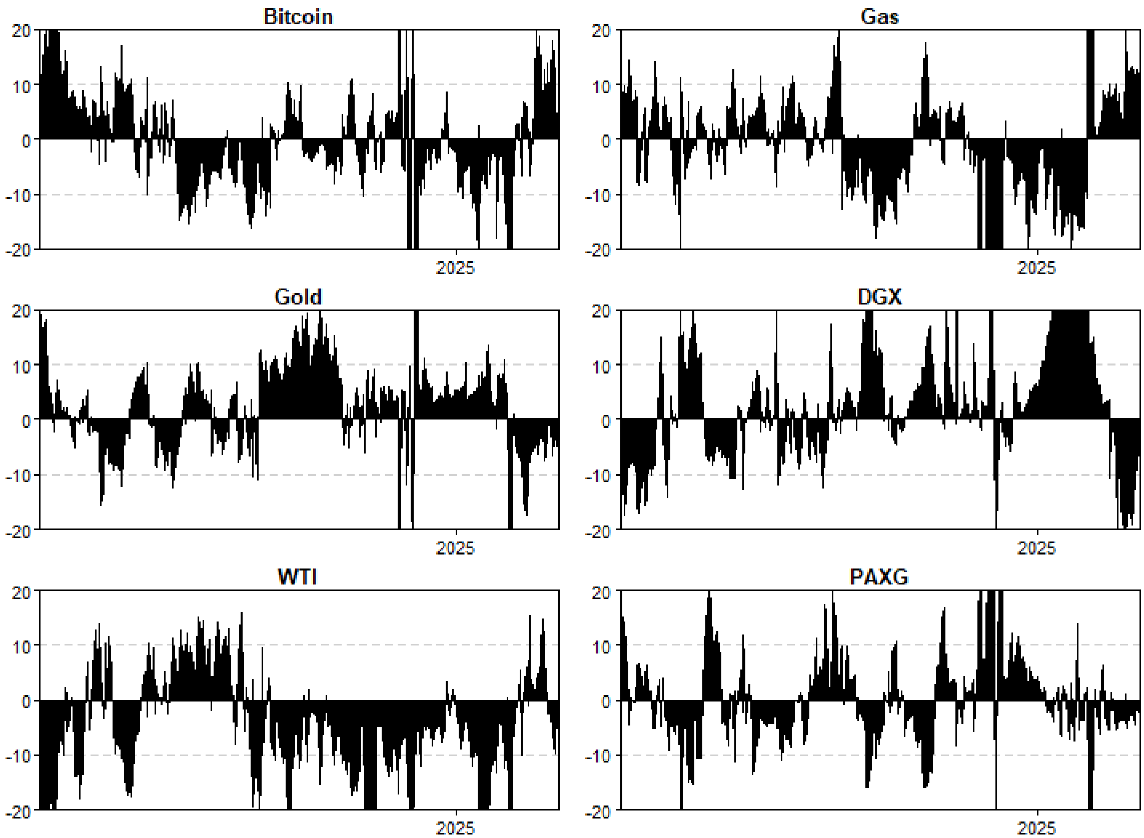


Figure 2: Net total connectedness

From Figure 2, Bitcoin exhibits alternating phases of transmitting and receiving shocks. In late 2023 and early 2024, it functions largely as a net receiver, while in 2025 it transitions into a net transmitter, particularly during the period of rising systemic risk, suggesting its growing influence in the return spillover structure. Gas appears volatile but plays a predominantly net receiver role for most of the sample. However, in 2025, it displays sharp positive spikes, indicating a temporary shift to a net transmitter position, possibly reflecting heightened energy market tensions or policy-related shocks.

Gold consistently alternates roles but notably acts as a net transmitter during much of 2024, especially in episodes of global uncertainty. This supports its role as a safe-haven asset, exerting influence over others during times of stress. However, by early 2025, it returns to a more neutral or receiving position. DGX, a gold-backed digital token, shifts from being a weak net receiver to a strong net transmitter, particularly in the latter part of 2024. Its role becomes more pronounced around the major connectedness spike in March 2025, suggesting its growing relevance in systemic transmission.

WTI (Crude Oil) remains largely a net receiver throughout the period, reflecting its reactive nature to broader macroeconomic and financial shocks rather than acting as a driver. This aligns with oil's sensitivity to global demand conditions rather than financial market dynamics. PAXG, another gold-backed cryptocurrency, remains predominantly a net receiver, indicating that it is more influenced by other assets, particularly traditional gold and Bitcoin, than it is a source of shocks.

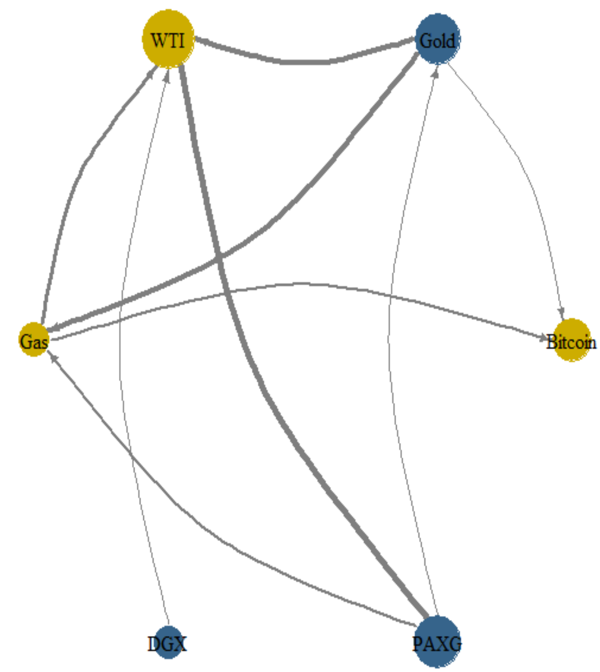


Figure 3. Net-Pairwise Directional Connectedness

The network graph in Figure 3 illustrates the directional spillovers among the financial assets by identifying their roles as either net transmitters or net receivers of shocks. Assets represented by blue nodes (PAXG, Gold, and DGX) are net transmitters, meaning they exert greater influence on other assets than they receive. In contrast, yellow nodes (Bitcoin, Gas, and WTI) are net receivers, indicating that their returns are more heavily shaped by external shocks within the system.

Among the transmitters, PAXG emerges as a dominant source of connectedness, exerting strong spillovers toward Gas and WTI. This suggests that the gold-backed digital asset plays an increasingly influential role in shaping the dynamics of traditional energy markets. Similarly, Gold functions as a major transmitter, sending significant shocks to both WTI and Gas. Its central role reaffirms its status as a systemic asset, often reacting swiftly to macroeconomic uncertainty and influencing broader market conditions. This suggests that Gold lost its safe-haven feature, corroborating the results of Cheema et al. (2020) and Jeribi and Snene-Manzli (2020). DGX, while also a net transmitter, shows a more moderate impact but still contributes to the return dynamics of Gas.

On the receiver side, Gas is the most exposed asset in the system, receiving substantial spillovers from Gold, PAXG, and DGX. Its sensitivity underscores its dependence on broader market forces, particularly those driven by monetary and commodity-linked instruments. WTI also acts as a prominent net receiver, absorbing shocks primarily from Gold and PAXG, reflecting its reactive nature to global risk sentiment. Bitcoin, although part of the network, plays a more marginal role with limited spillover intensity, suggesting a degree of insulation or decoupling from the other assets during the observed period.

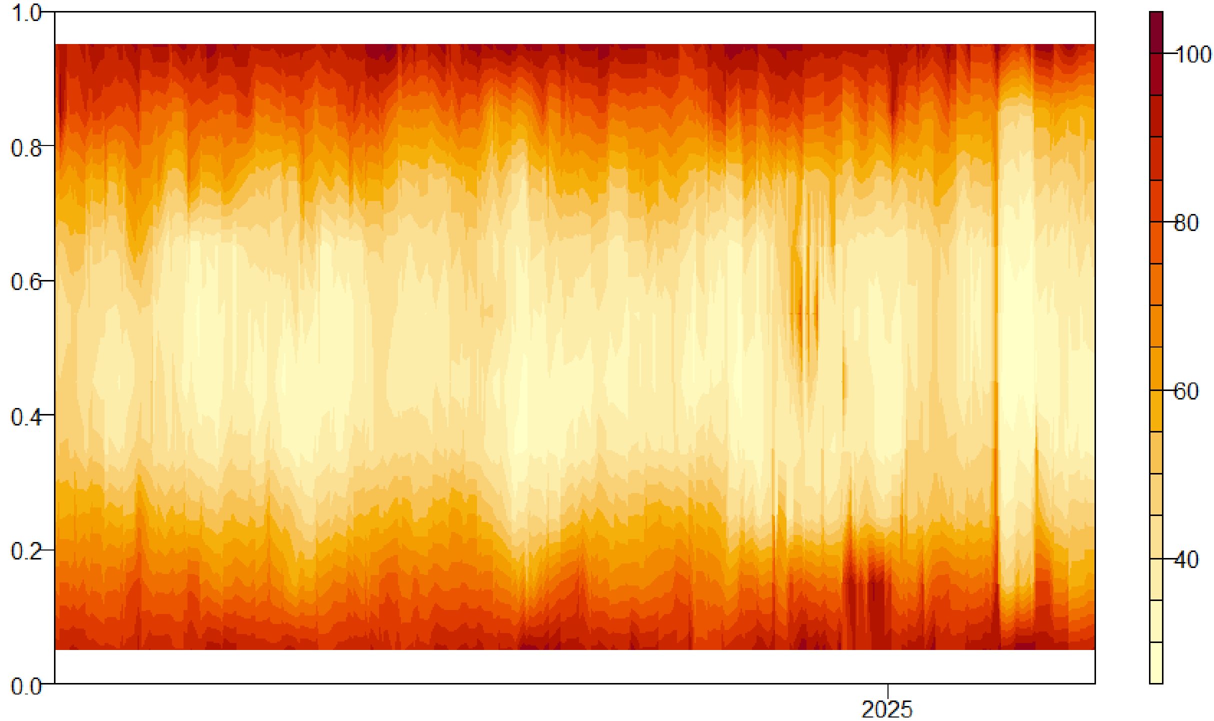


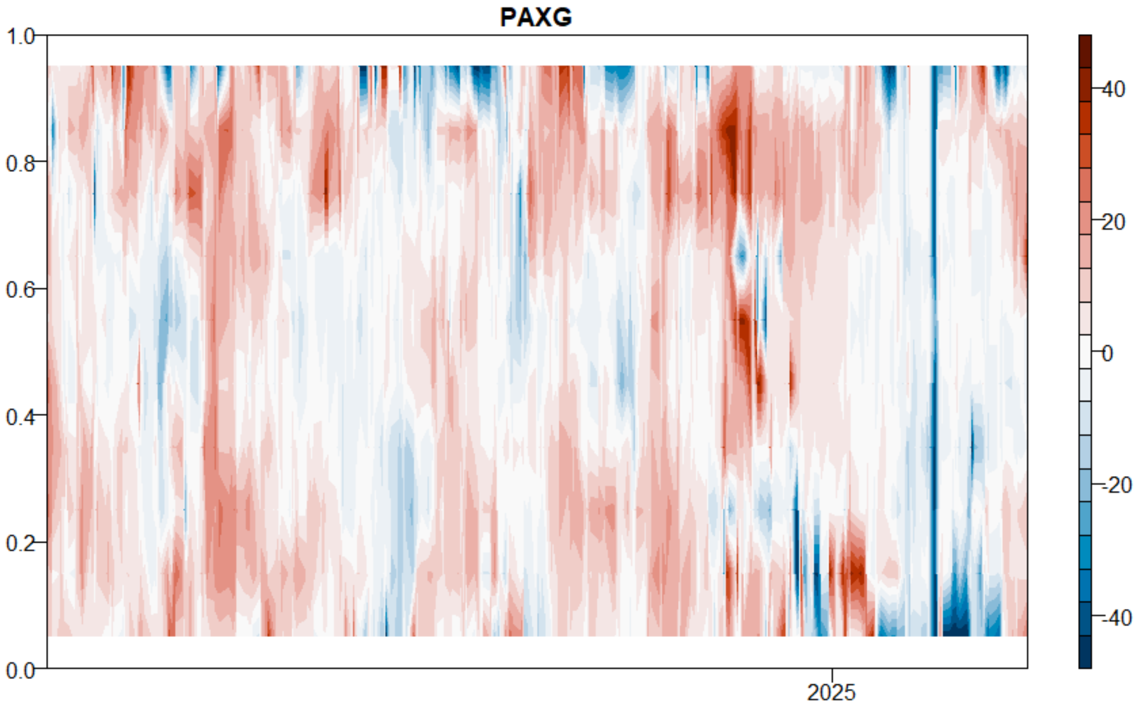
Figure 4: Quantile total connectedness

Figure 4 presents the Total Connectedness Index across quantiles over time for the system comprising Bitcoin, Gold, WTI, Gas, DGX, and PAXG. The vertical axis represents quantiles (ranging from 0.01 to 0.99), capturing the cross-market spillover structure under various market conditions, from extreme downturns to exuberant rallies. The color scale reflects the magnitude of total connectedness, with darker shades indicating stronger spillover effects.

The heatmap exhibits a pronounced U-shaped pattern across quantiles. Specifically, total connectedness is significantly higher in the lower ($\tau < 0.2$) and upper ($\tau > 0.8$) quantiles, corresponding respectively to bear and bull market conditions. In contrast, connectedness weakens in the median quantiles ($\tau \approx 0.5$), where market dynamics are relatively calm. This pattern highlights the state-dependent nature of systemic interdependence, wherein asset linkages intensify during periods of market stress or exuberance and weaken during normal times (Blanka and Karolina, 2020). These findings are consistent with the literature on nonlinear spillovers, which suggests that diversification benefits tend to diminish precisely during market extremes, when they are most needed.

Temporally, the heatmap indicates that from early 2023 through mid-2024, connectedness remains relatively stable and moderate across most quantiles. However, beginning in late 2024, and particularly in early 2025, the system experiences surges in total connectedness, especially in the tails of the distribution. These episodes likely coincide with periods of elevated uncertainty, such as geopolitical tensions, energy market shocks, or disruptive macroeconomic announcements (e.g., U.S. trade tariffs or monetary policy shifts). The increase in connectedness during these periods suggests heightened systemic risk, as shocks originating in one market are more readily transmitted to others.

Overall, the quantile-based total connectedness analysis provides important insights into the nonlinear and regime-sensitive nature of inter-asset relationships. It underscores the need for risk management strategies that account not only for time variation but also for asymmetries in market behavior across the return distribution.


PAXG
1.0
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0.6
0.4
0.2
0.0
2025
40
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0
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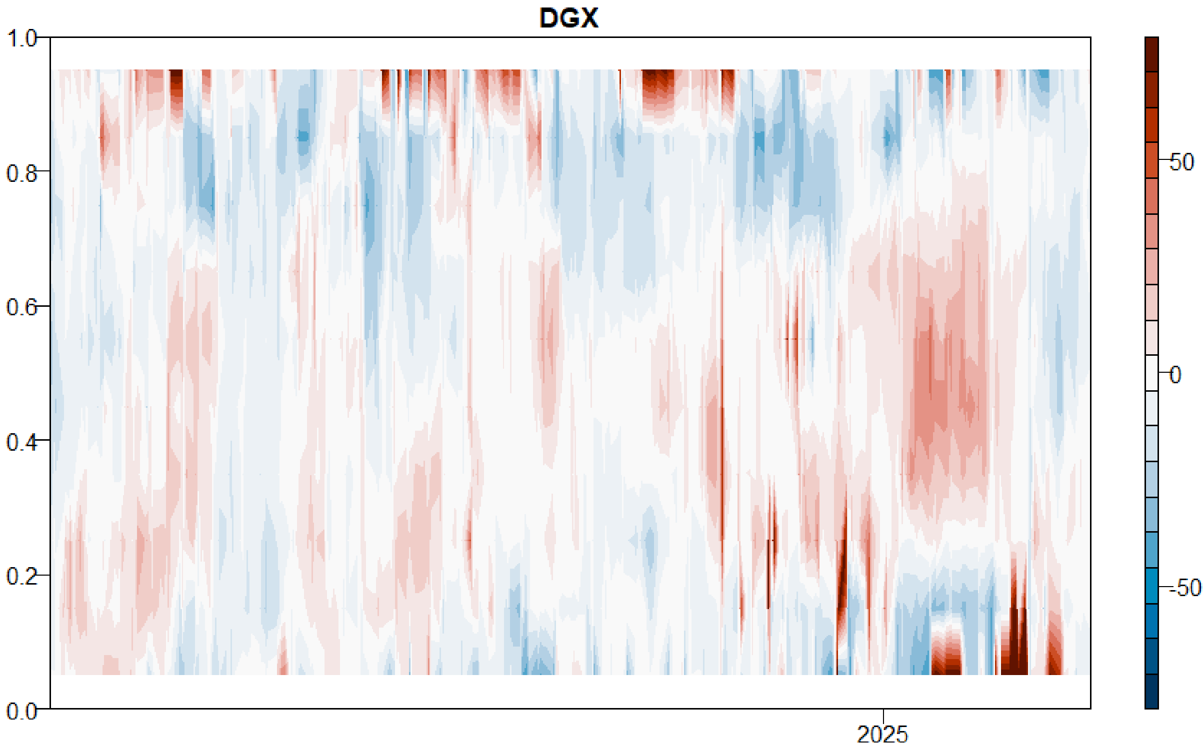
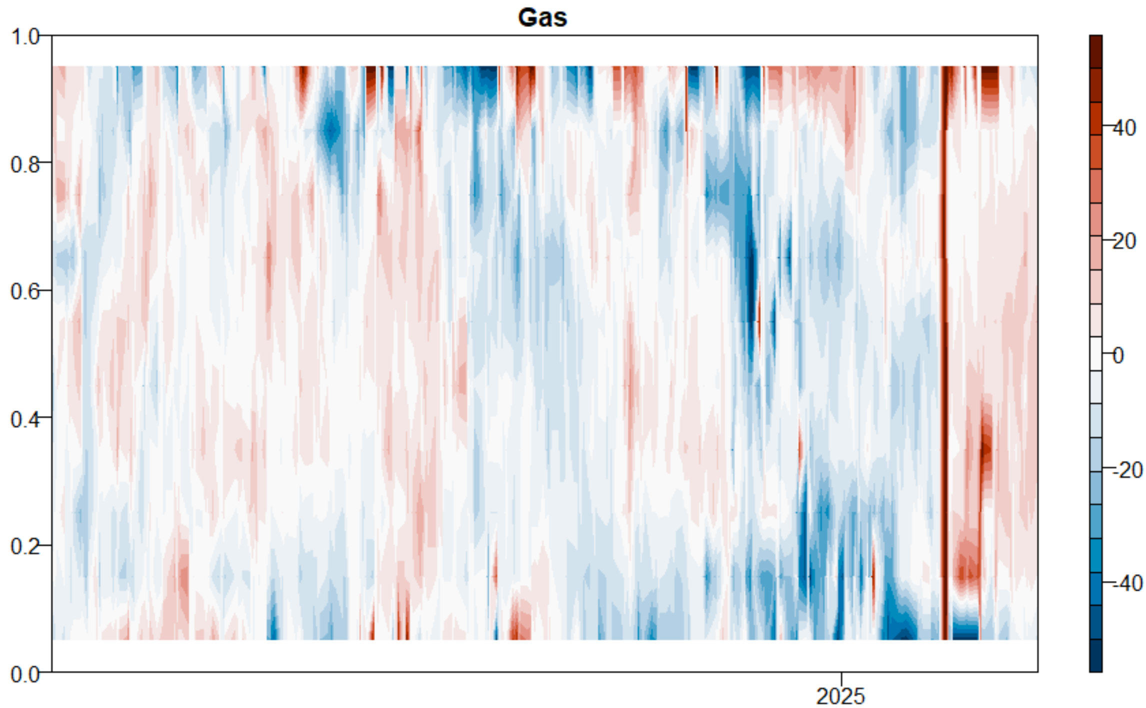
-40


DGX
1.0
0.8
0.6
0.4
0.2
0.0
2025
50
0
-50


Gas
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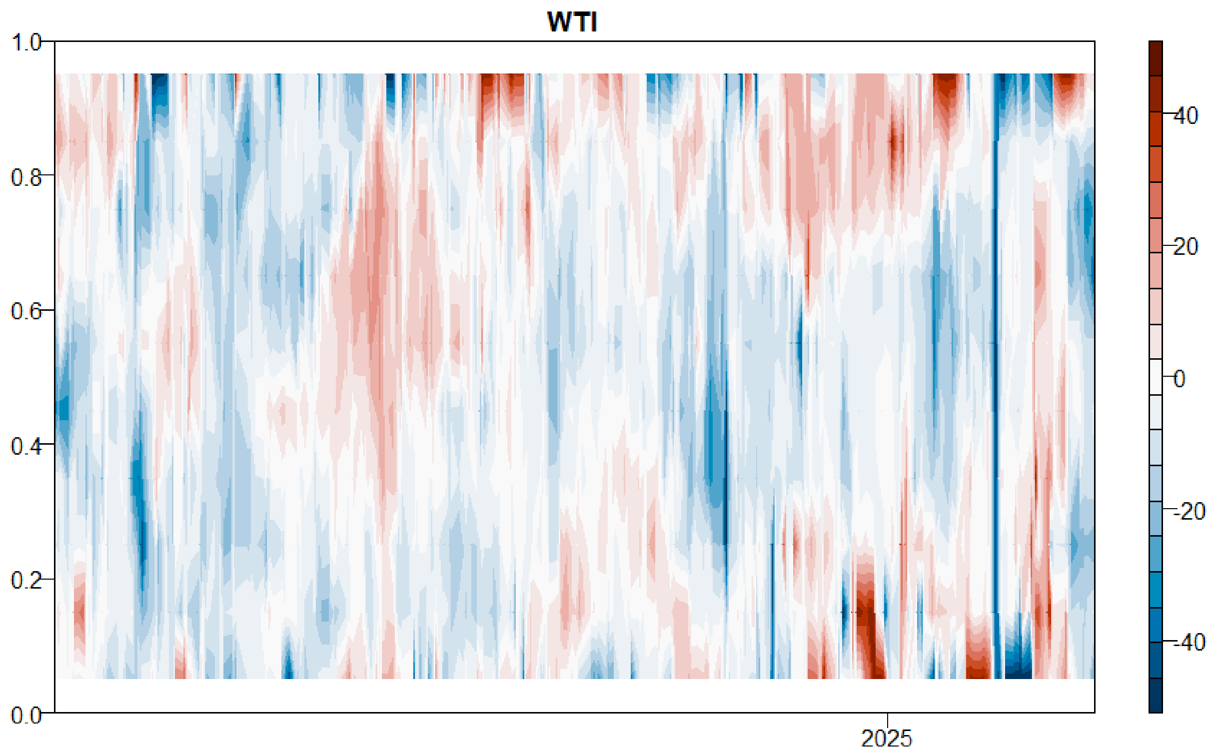
0.6
0.4
0.2
0.0
2025
40
20
0
-20
-40


WTI
1.0
0.8
0.6
0.4
0.2
0.0
2025
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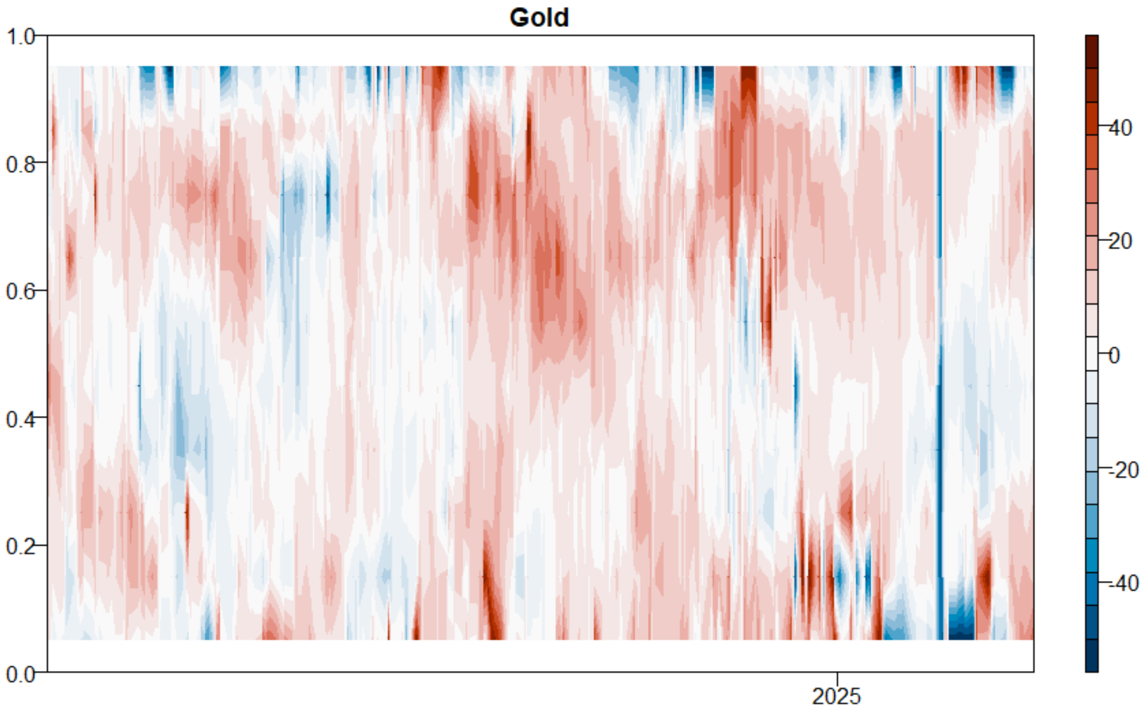
20
0
-20
-40


Gold
1.0
0.8
0.6
0.4
0.2
0.0
2025
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20
0
-20
-40

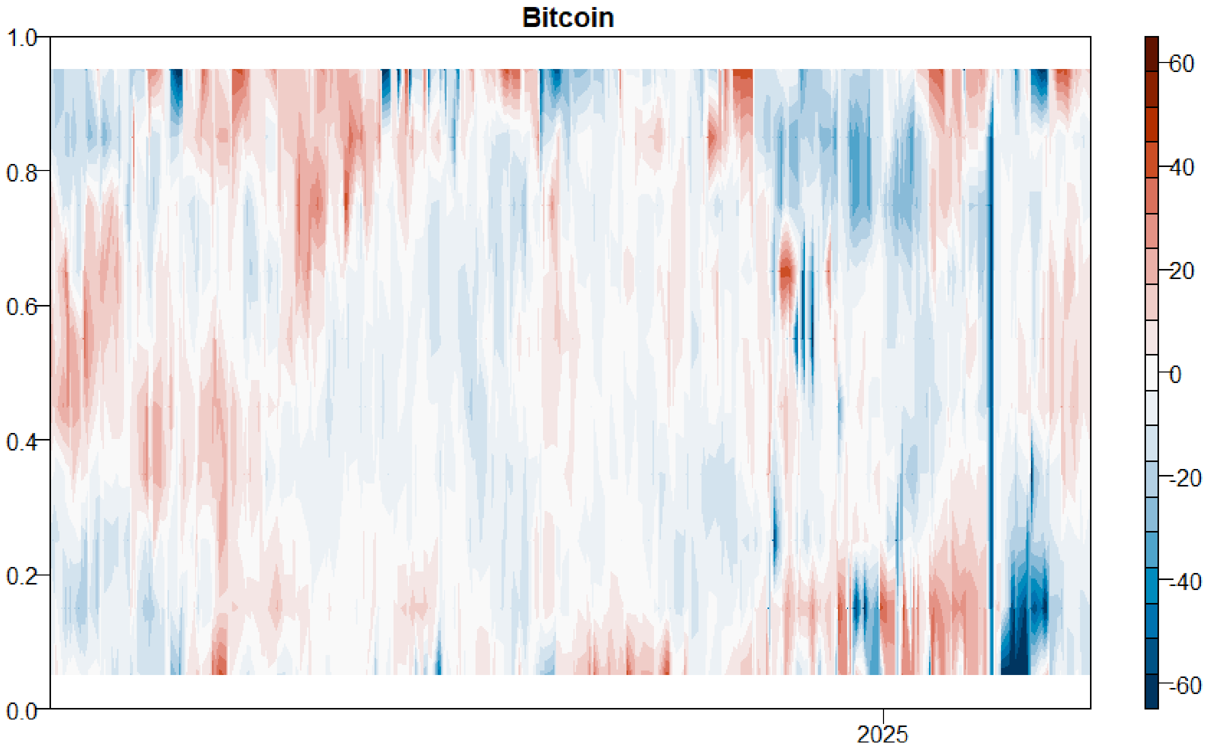
Bitcoin
1.0
0.8
0.6
0.4
0.2
0.0
2025
60
40
20
0
-20
-40
-60

Figure 5: Total net connectedness through quantiles

The quantile-based net connectedness analysis in Figure 5 reveals clear behavioral clustering among the six assets, Bitcoin, Gold, WTI, Gas, DGX, and PAXG, based on their systemic roles across different market regimes. Rather than acting independently, several assets exhibit similar spillover dynamics, allowing for meaningful grouping in terms of transmission intensity and responsiveness to external conditions.

Gold and PAXG consistently display positive net connectedness, particularly in the upper quantiles of the return distribution. This indicates that they act as dominant net transmitters of shocks during bullish or expansionary periods, influencing the broader system. Their systemic importance is evident in their ability to propagate volatility across markets, especially under conditions of heightened risk appetite or monetary shifts. DGX, while similar in nature as a tokenized gold asset, shows a more moderate and less persistent transmission profile. Compared to Gold and PAXG, DGX appears as a weaker transmitter, participating in volatility propagation during certain periods but with lower magnitude and consistency.

On the other side of the connectedness spectrum, WTI, Gas, and Bitcoin tend to act as net receivers, particularly in the tails of the distribution. Their roles are largely event-driven, with net connectedness shifting in response to specific geopolitical, macroeconomic, or market stress episodes. Gas and oil, in particular, show consistently negative net connectedness across most quantiles and time periods, indicating that they primarily absorb external shocks rather than generate them. Their behavior underscores the reactive nature of energy commodities, which are often influenced by global demand-supply conditions, policy decisions, and geopolitical uncertainty.

Bitcoin presents a distinct profile. While it tends to act as a net receiver in lower quantiles, especially during turbulent phases, it adopts a more neutral or balanced role in the median quantiles. This neutrality becomes particularly noticeable during 2025, where Bitcoin does not appear to be a dominant transmitter nor a strong receiver, suggesting a transitional or decoupled status during periods of relative market stability. However, in the upper quantiles, Bitcoin occasionally exhibits positive net connectedness, pointing to its limited but growing influence in bullish markets.

These findings highlight the importance of accounting for both quantile and temporal dimensions when assessing inter-asset spillovers, as asset behavior and systemic roles vary significantly across different market states.

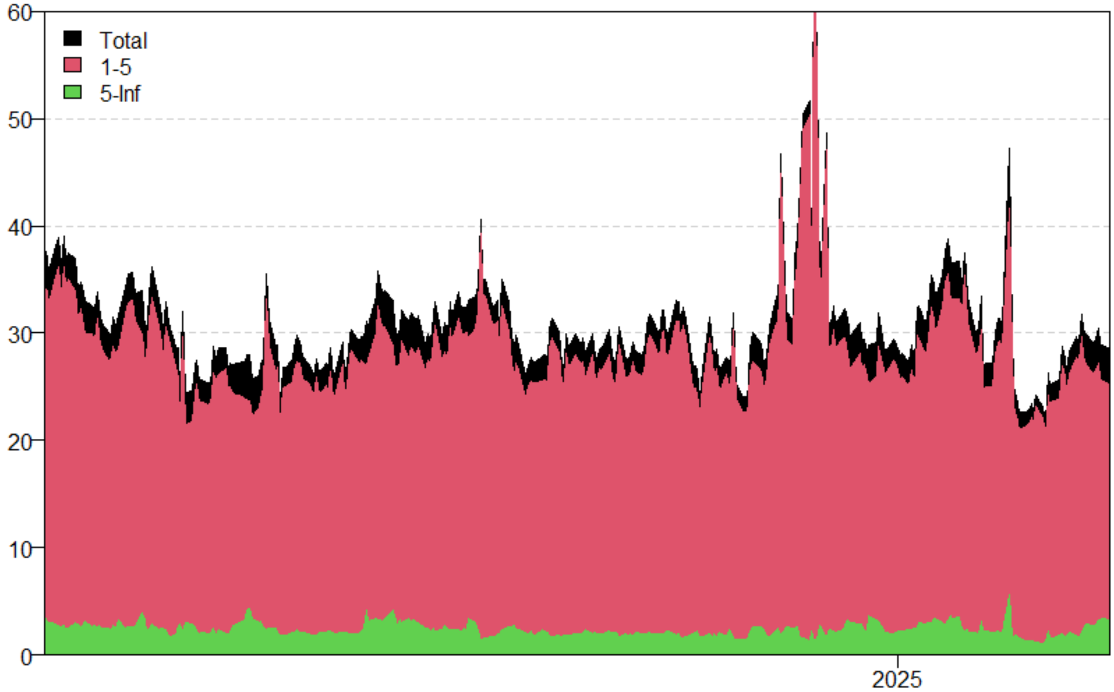

Figure 6: Total connectedness through time frequencies

The decomposition of total connectedness across frequencies in Figure 6 reveals that the interconnectedness among the studied assets is largely dominated by short-term dynamics throughout the sample period. Most of the spillover effects are concentrated within the 1–5 day frequency band, as indicated by the wide red area, suggesting that return interactions and volatility transmissions are predominantly driven by short-lived market reactions. This reflects a system that is highly sensitive to immediate news, short-term trading behavior, and transitory shocks.

Despite the dominance of short-term spillovers, long-term connectedness (beyond 5 days), shown in green, maintains a stable yet relatively low presence for most of the period. However, a gradual increase in this component is observed toward the end of the sample, particularly from late 2024 into early 2025. This trend implies that long-term interdependencies among the assets become more relevant during and following periods of heightened uncertainty, possibly reflecting more persistent structural adjustments linked to macroeconomic or geopolitical developments.

The spikes in the total connectedness index, particularly those seen in early 2025, are mainly attributed to sharp increases in short-term connectedness. This indicates that during crisis episodes or abrupt market events, contagion effects are mostly immediate and concentrated in the high-frequency domain. The long-term component during these peaks remains relatively muted, suggesting that while systemic reactions are strong, they are not necessarily enduring.

Overall, the frequency decomposition reveals a system that is primarily reactive and short-term oriented but exhibits signs of growing long-term synchronization in the aftermath of stress. This highlights the importance of managing both high-frequency volatility and lower-frequency co-movements, especially when shocks begin to embed into the structural behavior of the market.

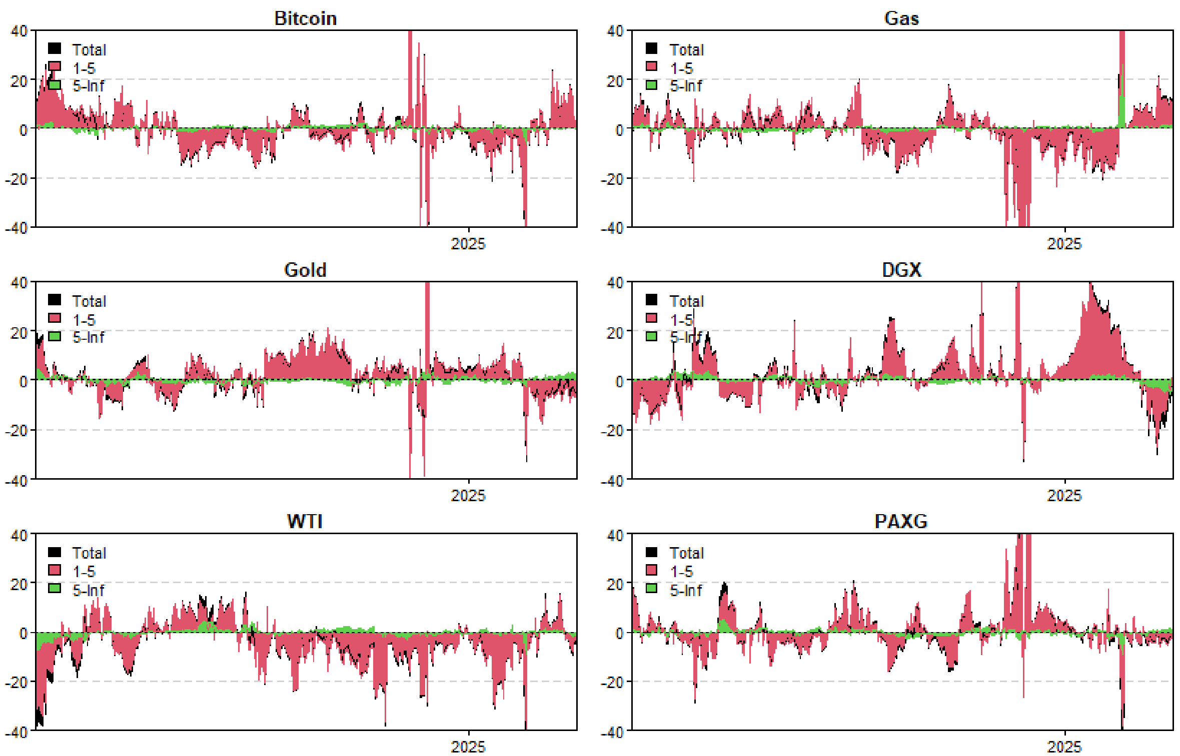

Figure 7: Net total connectedness through frequencies

Figure 7 displays the net connectedness of each asset (Bitcoin, Gas, Gold, DGX, WTI, and PAXG) decomposed across frequency bands, short-term (1–5 days), long-term (5 days and more), and total net connectedness, over time. This decomposition allows us to analyze not only whether each asset is a net transmitter or receiver of shocks, but also the temporal horizon at which this influence or vulnerability manifests.

Across all assets, the short-term component (in red) dominates the net connectedness profiles, indicating that most systemic interactions are driven by high-frequency spillovers. These short-lived dynamics suggest that markets are highly sensitive to immediate news and short-run volatility bursts, particularly during periods of stress.

Bitcoin shows relatively balanced net connectedness overall, fluctuating between weak transmitter and receiver roles depending on the market context. Notably, its largest spikes in net connectedness occur abruptly and are short-lived, dominated entirely by short-term components. This reinforces Bitcoin's role as an event-sensitive, short-term reactive asset rather than a consistent source of systemic influence.

Gas and WTI exhibit prolonged periods as net receivers, especially during crisis conditions. Their net connectedness is significantly negative across most of the sample, suggesting that energy commodities primarily absorb shocks rather than transmit them. This role is largely confined to the short-term band, confirming their responsiveness to fast-moving, event-driven market dynamics such as geopolitical tensions or supply disruptions.

Gold stands out as a persistent net transmitter, particularly in the short-term component. It steadily contributes to system-wide connectedness across nearly the entire sample, reinforcing its systemic importance. However, compared to other assets, Gold also displays a more stable profile with fewer extreme spikes, reflecting its dual role as both a safe haven and a volatility carrier.

DGX and PAXG, the tokenized gold assets, mirror some features of Gold but with reduced intensity. DGX, in particular, demonstrates modest net transmitter behavior during calm periods and heightened short-term influence during specific volatility clusters. PAXG displays more erratic behavior, alternating between transmitter and receiver roles, but remains short-term dominant throughout. These patterns suggest that while tokenized gold assets echo the dynamics of physical gold, they exhibit greater sensitivity to crypto-market volatility and idiosyncratic, token-specific factors.

In summary, the frequency-decomposed net connectedness analysis highlights three behavioral clusters: (1) Gold as a stable, dominant transmitter; (2) Bitcoin, DGX, and PAXG as short-term, event-responsive actors; and (3) WTI and Gas as consistent net receivers, especially in high-frequency regimes. These findings emphasize the importance of frequency-aware modeling in understanding financial spillovers and the differentiated roles assets play across temporal horizons.

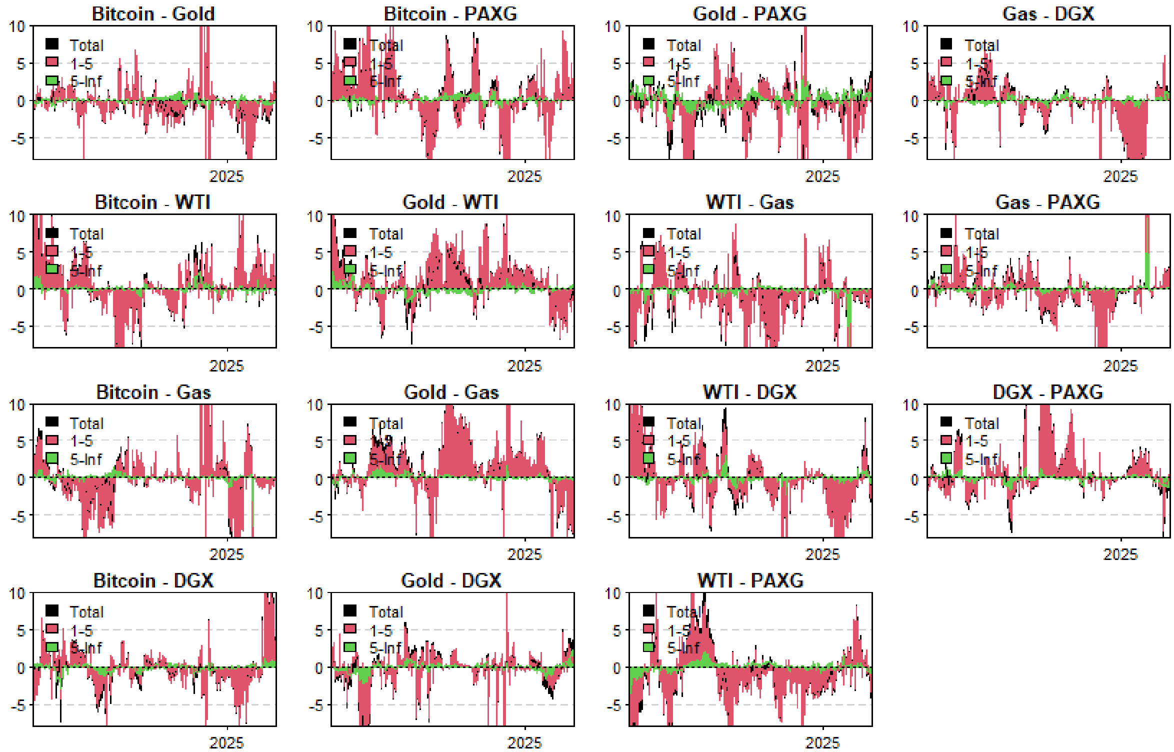

Figure 8: Net pairwise directional connectedness

The net pairwise connectedness analysis provides a detailed view of how individual assets interact with one another over time and across frequencies. The decomposition distinguishes between short-term (1–5 days) and long-term (beyond 5 days) spillovers, revealing the direction and persistence of information transmission between each pair of assets. Across most pairwise relationships, short-term spillovers dominate, confirming that systemic interactions are largely event-driven and reactive in nature.

Gold consistently emerges as a key volatility transmitter in its pairwise relationships, particularly with its tokenized counterparts, PAXG and DGX. In both the Gold–PAXG and Gold–DGX panels, net connectedness is strongly positive and concentrated in the short term, indicating that Gold leads these assets in transmitting shocks. This reflects Gold's traditional role as a systemic anchor, with PAXG and DGX essentially echoing its dynamics, albeit with less intensity and greater sensitivity to crypto-market conditions.

In contrast, Bitcoin's relationships with other assets display more fluctuation. Its net connectedness alternates between positive and negative, particularly in relation to Gold, WTI, and Gas. These reversals suggest that Bitcoin's systemic role is context-dependent and shaped by specific events or volatility episodes. While it occasionally acts as a transmitter in bullish or speculative regimes, it more frequently functions as a net receiver, especially under stress. The Bitcoin–PAXG and Bitcoin–DGX relationships remain weak and short-term in nature, highlighting the structural gap between decentralized digital currencies and tokenized commodities.

Gas and WTI are predominantly net receivers in most of their bilateral connections, particularly from Gold and its digital analogues. The negative net connectedness in these relationships underscores the vulnerability of energy assets to external financial shocks. Their sensitivity is especially evident during periods of market stress, where they absorb volatility rather than propagate it. Long-term spillovers from these assets are minimal, suggesting that their systemic role remains transitory and externally driven.

Finally, the DGX-PAXG relationship reflects moderate and balanced spillover activity, largely confined to short-term horizons. Although both assets are tokenized representations of gold, their interaction does not exhibit the same dominant transmission structure observed with physical gold. This implies that while they share some common risk factors, they are not perfectly aligned.

Table 3: Total connectedness through frequencies

	Bitcoin.Total	Gold.Total	WTI.Total	Gas.Total	DGX.Total	PAXG.Total	FROM.Total
Bitcoin	88.19	1.84	1.84	2.19	2.58	3.38	11.81
Gold	1.40	56.57	2.56	0.97	1.01	37.50	43.43
WTI	1.56	4.22	86.47	2.04	1.83	3.87	13.53
Gas	1.46	2.54	1.00	91.85	1.52	1.62	8.15
DGX	2.26	1.19	1.21	1.37	93.18	0.79	6.82
PAXG	2.99	36.98	2.20	0.82	0.46	56.55	43.45
TO	9.67	46.77	8.81	7.39	7.41	47.15	127.20
Inc.Own	97.86	103.34	95.28	99.24	100.58	103.70	cTCI/TCI
Net	-2.14	3.34	-4.72	-0.76	0.58	3.70	25.44/21.20
NPDC	0.00	4.00	1.00	2.00	3.00	5.00	

Table 4: Total connectedness through frequencies

	Bitcoin.1-5	Gold.1-5	WTI.1-5	Gas.1-5	DGX.1-5	PAXG.1-5	FROM.1-5
Bitcoin	81.82	1.77	1.76	2.15	2.28	3.19	11.15
Gold	1.26	51.78	2.30	0.91	0.91	33.99	39.35

WTI	1.46	4.10	79.05	1.90	1.69	3.79	12.94
Gas	1.36	2.31	0.94	84.82	1.39	1.47	7.46
DGX	2.06	1.08	1.12	1.27	85.75	0.71	6.23
PAXG	2.76	33.61	2.04	0.75	0.42	51.93	39.57
TO	8.88	42.86	8.16	6.96	6.68	43.15	116.70
Inc.Own	90.71	94.64	87.21	91.78	92.42	95.08	cTCI/TCI
Net	-2.26	3.51	-4.78	-0.49	0.45	3.58	23.34/19.45
NPDC	0.00	4.00	1.00	2.00	3.00	5.00	

Table 5: Total connectedness through frequencies

	Bitcoin.5-Inf	Gold.5-Inf	WTI.5-Inf	Gas.5-Inf	DGX.5-Inf	PAXG.5-Inf	FROM.5-Inf
Bitcoin	6.36	0.07	0.07	0.04	0.29	0.19	0.66
Gold	0.14	4.79	0.26	0.06	0.10	3.51	4.08
WTI	0.10	0.12	7.42	0.14	0.15	0.08	0.59
Gas	0.11	0.23	0.07	7.03	0.14	0.15	0.69
DGX	0.21	0.12	0.09	0.10	7.43	0.08	0.59
PAXG	0.23	3.37	0.16	0.08	0.05	4.61	3.89
TO	0.78	3.90	0.65	0.43	0.73	4.01	10.50
Inc.Own	7.15	8.70	8.08	7.46	8.16	8.62	cTCI/TCI
Net	0.12	-0.18	0.06	-0.26	0.14	0.12	2.10/1.75
NPDC	4.00	2.00	2.00	1.00	3.00	3.00	

The frequency-based connectedness tables offer a detailed decomposition of systemic interactions across the full spectrum, as well as over short-term (1-5 days) and long-term (5 days and above) horizons. The results show that connectedness in the system is primarily driven by high-frequency dynamics, with long-term spillovers playing a much smaller role.

In the overall connectedness matrix (Table 3), Gold and PAXG emerge as the most influential transmitters, contributing 46.77 and 47.15, respectively, to the "TO" spillovers. Their corresponding "FROM" values are also high, but the net connectedness is positive for both assets (+3.34 for Gold and +3.70 for PAXG), indicating that they are net transmitters in the system. Bitcoin, by contrast, is a net receiver (-2.14), absorbing more volatility than it transmits. Similar net receiver profiles are observed for WTI (-4.72) and Gas (-0.76), reinforcing their roles as passive actors within the network. DGX appears relatively neutral but slightly transmitter-biased (+0.58), positioning it between the dominant transmitters (Gold/PAXG) and systemic absorbers (WTI/Gas).

In terms of short-term connectedness (Table 4), the dynamics are largely consistent with the full-sample results. The contribution of short-term frequencies accounts for the vast majority of overall connectedness. For instance, PAXG and Gold continue to dominate the system in terms of "TO" values (43.15 and 42.86, respectively), with positive net spillovers of +3.58 and +3.51. Bitcoin (-2.26), WTI (-4.78), and Gas (-0.49) remain net receivers. This confirms that the system is highly reactive in the short term, with rapid volatility transmission primarily driven by Gold and its tokenized counterpart, PAXG. The short-term connectedness index (cTCI) reaches 19.45, accounting for over 91% of the total system-wide connectedness (19.45 out of 21.20), emphasizing the dominance of high-frequency contagion.

Turning to long-term connectedness (Table 5), the magnitude of spillovers drops substantially across all asset pairs. The total system-wide connectedness at this horizon is only 1.75, indicating that long-term spillovers play a secondary role in systemic transmission. While Gold and PAXG still show meaningful "TO" spillovers (3.90 and 4.01, respectively), their net spillovers become almost neutral or slightly negative (-0.18 for Gold and +0.12 for PAXG), highlighting the diminished dominance of even the most influential transmitters over longer horizons. Bitcoin, DGX, and WTI each show near-zero net spillover values, reinforcing the idea that long-run systemic influence is weakly distributed and less hierarchical than in the short term.

Finally, the Net Pairwise Directional Connectedness (NPDC) scores further illustrate the transmission hierarchy. In both the overall and short-term matrices, PAXG, Gold, and DGX exhibit the highest NPDC rankings (5.00, 4.00, and 3.00, respectively), confirming their strong directional influence. In contrast, Bitcoin and WTI consistently score lower (NPDC ≤ 1), underscoring their roles as residual or reactive players.

In conclusion, the decomposition across frequencies shows that short-term connectedness dominates systemic dynamics, with Gold and PAXG acting as central transmitters. Energy commodities (WTI, Gas) and Bitcoin mainly serve as net receivers, particularly in turbulent conditions. Over longer horizons, the intensity of connectedness diminishes considerably, suggesting that market interconnectedness is largely tactical and transient rather than persistent or structural.

Conclusion

This study provides a comprehensive evaluation of connectedness dynamics across a diverse set of assets, including digital, tokenized, financial, and energy, by employing a dual quantile-frequency connectedness framework. The results confirm that systemic risk is both state-dependent and frequency-sensitive. Total connectedness intensifies significantly during market extremes, validating the collapse of diversification benefits precisely when they are most needed.

Gold and its tokenized derivatives (PAXG and, to a lesser extent, DGX) emerge as consistent net transmitters of volatility, underscoring their central role in shaping systemic interactions. While PAXG closely mirrors the behavior of physical gold, DGX plays a more moderate role in the transmission structure. Conversely, Bitcoin, WTI, and Gas primarily act as net receivers, with their connectedness highly sensitive to event-specific shocks and macro-political developments.

Frequency decomposition further demonstrates that short-term (1–5 day) spillovers account for the bulk of interconnectedness, driven by fast-moving, reactive contagion. Long-term spillovers remain comparatively weak but show a gradual increase during crisis periods, suggesting that persistent structural dependencies can emerge following geopolitical or macroeconomic disruptions.

Overall, the findings offer nuanced insights into the transmission mechanisms of systemic shocks and highlight the rising systemic relevance of tokenized gold instruments. This research contributes to the literature by providing an integrated framework capable of capturing asymmetric, nonlinear, and horizon-specific interdependencies, offering practical implications for asset allocation, portfolio hedging, and systemic risk oversight in an increasingly complex financial ecosystem.

Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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