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Mapping green market dynamics: Insights into sustainable sectors and strategic tech minerals

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Abstract: This study explores the spillover dynamics and interconnectedness among traditional energy markets, eco-friendly indices, and strategic minerals under varying economic conditions. Quantile connectedness measures are employed to capture asymmetric spillover effects across adverse (5th percentile), normal (median), and boom (95th percentile) conditions. To ensure robustness, a Quantile Vector Autoregression (QVAR) framework is utilized to validate the findings. The results reveal significant heterogeneity: traditional energy markets dominate as spillover transmitters during boom periods, while eco-friendly indices and strategic minerals exhibit balanced or dependent roles across quantiles. Gasoline and Tellurium emerge as key transmitters in stressed conditions, whereas Coal and Gas Oil play dominant roles during bullish markets. These findings offer valuable insights into the dynamics of market interdependence, emphasizing the need for tailored risk management strategies. Academically, this study contributes to the literature on connectedness, while offering practical implications for energy policy and sustainable market strategies.

Keywords: eco-friendly sustainable markets; strategic tech minerals; environmental sustainability; quantile connectedness

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1. Introduction

For decades, the issue of climate change has compelled policymakers, governments, regulatory bodies, and environmentalists to address significant climate challenges. This has led to directives promoting clean energy sources facilitated by energy transition metals and clean energy markets, alongside efforts to reduce reliance on polluting energy sources to safeguard against environmental degradation (Li et al., 2023). Numerous nations are actively pursuing environmental sustainability through various domestic and international initiatives. The International Energy Agency (2021) spearheads efforts toward clean and renewable energy solutions to alleviate environmental pressures. Contemporary literature affirms that global environmental changes are abrupt, unpredictable, and steadily escalating, primarily due to the persistent use of non-renewable energy resources like fossil fuels, contributing to an increasing carbon footprint (Ugochukwu et al., 2022). Adopting eco-friendly markets and reducing reliance on polluting resources curtails environmental degradation.

Conversely, non-eco-friendly markets such as fuel oil, heating oil, crude oil, and natural gas are deeply entrenched in the financial system (Elsaid et al., 2021) and play a pivotal role in the economic landscape as well (Shu et al., 2023; Chen et al., 2018). Originating from non-renewable and environmentally harmful sources, these markets amplify potential threats to the global ecosystem, including global warming, greenhouse gas emissions (GHGs), and persistent climate change. Despite their firm integration into the market, eliminating dirty energy market usage and foreign exchange transactions seems unfeasible. However, sustained efforts by governments, policymakers, and regulatory bodies can facilitate a transition from dirty to clean energy markets (Tagizadeh-Hesary et al., 2021). As a result, clean energy markets are emerging as environmentally friendly and socially responsible investments poised to contribute to a future characterized by climate resilience.

Persistent efforts aimed at energy transitions hold the potential to mitigate the catastrophic impacts of climate change by steering towards the utilization of energy metals (Wang et al., 2019). These metals are committed to recyclability, energy efficiency, and genuine renewability. Research highlights the crucial role of environmentally sustainable metals in driving energy transitions, with global natural resources sufficient to meet the challenges of energy consumption and depletion worldwide. Driven by global decarbonization efforts, technological advancements like digitalization and smart grids, and rising societal expectations, investors are increasingly motivated to reduce the carbon footprints of their businesses. The International Renewable Energy Agency (IRENA) indicates that incorporating sustainable metals and renewable technologies can significantly lower electricity costs by 25-60%, depending on the specific technologies used. As a result, energy metals, also known as energy transition metals, are set to replace traditional metals, fostering sustainable development and supporting the move towards a greener future.

Strategic tech minerals encompass various metallic elements and minerals fundamental to the functioning of clean energy technologies and the transition to sustainable energy sources.[1] These metals are known for their unique properties, making them vital for energy-related applications. Prominent examples of metals include lithium, cobalt, nickel, rare earth elements (such as neodymium and dysprosium), and copper. One primary role of strategic tech minerals is in energy storage solutions. They enable the efficient storage and release of electricity, addressing the intermittent nature of renewable energy sources like wind and solar. Strategic tech minerals contribute to developing advanced batteries and supercapacitors that store energy during high-demand periods or when renewable energy generation is low. The availability of these metals has geopolitical implications, as countries and regions with significant reserves may hold strategic advantages in the clean energy transition, impacting the supply and pricing of these metals and affecting global energy markets. Given the growing importance of sustainability in the energy transition, developing recycling methods for strategic tech minerals to reduce waste and reliance on primary mining is crucial.

Subsequently, it is imperative to address research inquiries: How does quantile connectedness vary among strategic tech minerals, eco-friendly energy markets, and conventional energy markets across different quantiles? If quantile connectedness is observed, how do markets propagate this connectedness? Is there a marked difference in the mechanism of spillover direction when shaping static or dynamic connectedness? If so, what role do global circumstances and events play in these spillovers? All these queries form a robust foundation for conducting a quantile connectedness and Quantile Value at Risk (QVaR) analysis, enhancing our understanding of the magnitude and direction of spillovers within the context of metals and eco-friendly markets. Accordingly, policymakers and regulatory authorities can make well-informed decisions and implement suitable regulatory frameworks by identifying which market is the source or recipient of spillovers of strategic tech minerals and eco-friendly markets. For investors, the asymmetric analysis affirms additional benefits for portfolio managers and investors,

[1] The metals included in this study are considered strategic due to their critical applications in clean energy transitions and technological innovation. For instance, Germanium and Tellurium are used in the production of high-efficiency photovoltaic cells for solar panels, while Cobalt plays a key role in lithium-ion batteries for electric vehicles. Indium is integral to the manufacturing of semiconductors and touchscreens, and Gallium is crucial for LED technology and advanced telecommunications. These materials are indispensable for emerging green technologies and are vital for meeting the increasing global demand for sustainable and high-tech solutions.

particularly when informed about these metals' specific advantages in resource stabilization.

The existence of connectedness among eco-friendly markets, metals, and non-eco-friendly markets at different quantiles is a complex and multifaceted phenomenon influenced by various factors and dynamics within the global energy landscape. The study aims to observe distinct quantile connectedness in the performance of strategic tech minerals, eco-friendly markets, and non-eco-friendly markets at various quantiles. These differences are rooted in the contrasting fundamentals and drivers that underpin each sector. In eco-friendly markets, such as those related to renewable energy and electric vehicles, a notable skew is observed at higher quantiles. This is primarily due to the increasing global focus on sustainability and climate change mitigation, driving significant investments and policy support for eco-friendly technologies. Consequently, eco-friendly markets perform relatively better during extremely positive market events. Conversely, non-eco-friendly markets characterized by fossil fuels like coal, oil, and natural gas exhibit negative risk transmission at higher quantiles. They are susceptible to adverse shocks and display greater downside risk during extreme market conditions. This susceptibility is attributed to price volatility, geopolitical tensions, and environmental concerns, leading to divestment campaigns and regulatory pressures. Consequently, non-eco-friendly markets tend to experience substantial losses during market downturns.

Strategic tech minerals, essential components of eco-friendly technologies like lithium-ion batteries, present a mixed picture. While the demand for these metals has surged with the growth of eco-friendly markets, their supply chain constraints and geopolitical dependencies introduce significant uncertainty. This uncertainty can lead to asymmetric price movements at different quantiles, with potential supply disruptions causing price spikes during extreme events. However, it also benefits from positive sentiment during bull markets for eco-friendly energy. Moreover, regulatory interventions and policy changes are crucial in shaping these asymmetries. Government policies promoting eco-friendly energy adoption and carbon pricing mechanisms can enhance the positive skew in eco-friendly markets while adversely affecting non-eco-friendly markets.

This study contributes to the existing body of knowledge in several significant ways. Firstly, it pioneers utilizing these metals as an alternative to stabilize natural resources and mitigate environmental hazards. Secondly, the dataset incorporates various eco-friendly and non-eco-friendly energy markets to present a comprehensive overview, revealing their roles in resource allocation, stability, and sustainable development. Thirdly, we employ the quantile connectedness methodology introduced by Ando et al. (2022) to unveil market spillovers. Furthermore, we emphasize asymmetric risk spillovers at extreme lower, median, and extreme upper quantiles. Fourthly, we conducted the robustness analysis using the Quantile Vector Autoregression (QVAR) approach as it offers a comprehensive understanding of the dynamic relationships between multiple time series variables across different points in their distribution, capturing the behavior of these relationships under varying market conditions, including extreme events. By analyzing these relationships at different quantiles, QVAR helps identify how markets influence each other during market stress versus more stable periods, revealing significant spillover effects and interconnectedness among variables. Lastly, we offer meaningful implications for policymakers, government entities, regulatory bodies, environmental advocates, and investors.

The quantile connectedness analysis and the robustness check using the Quantile Vector Autoregression (QVAR) framework highlight spillovers' asymmetric and dynamic nature among traditional energy markets, eco-friendly indices, and strategic minerals across varying economic conditions. Traditional energy markets, such as Coal and Gas Oil, consistently emerge as dominant spillover transmitters during boom conditions, reflecting their amplified influence in high-demand scenarios. Conversely, eco-friendly indices like S&P CE and Wilder Hill CE exhibit balanced spillover roles, signaling their growing integration into global markets. Strategic minerals, including Germanium and Cobalt, are significant net receivers under adverse and extreme conditions, underscoring their vulnerability to external shocks. The QVAR framework confirms the robustness of these findings, reinforcing the systemic importance of traditional energy markets during positive market phases and the relative susceptibility of strategic minerals and renewable markets during stressed periods. These insights underscore the complex interdependence among markets.

The remaining study is structured as follows: Section 2 outlines our methodological approach; Section 3 elaborates on data and provides descriptive statistics; Section 4 details the empirical results; and Section 5 concludes the study.

2. Methodology

We employed specific methodological steps to obtain the desired results from the study. First, we measured the quantile connectedness across the markets to study spillovers at the median, extreme lower, and extreme upper quantiles, as proposed by Ando et al. (2022). Then, we employed quantile connectedness, combining the quantile VAR with the spillover approach of Diebold and Yilmaz (2012) to measure the connectedness of market volatilities at the median, extreme lower, and extreme upper quantiles.

2.1. Quantile Connectedness

Quantile connectedness is based on the Diebold-Yilmaz connectedness framework, augmented to account for different quantiles of the data distribution. This method captures the transmission of shocks across markets under varying conditions.

i) Variance decomposition matrix for quantile τ:

$$\theta_{ij}^{(\tau)} = \frac{\sigma_{ij}^{(\tau)}}{\sum_{k=1}^{N} \sigma_{ik}^{(\tau)}} \tag{1}$$

ii). Total connectedness at quantile τ:

$$C^{(\tau)} = \frac{\sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} \theta_{ij}^{(\tau)}}{N} \tag{2}$$

2.2 Quantile Vector Autoregression (QVAR)

Quantile Vector Autoregression (QVAR) is a method for analyzing the dynamics of multiple time series across different quantiles of the data distribution. This approach is particularly useful for identifying asymmetric relationships and spillover effects under extreme market conditions.

The QVAR model for a system of N variables at quantile τ can be expressed as:

$$Y_t^{(\tau)} = c^{(\tau)} + \sum_{p=1}^{P} A_p^{(\tau)} Y_{t-p} + \varepsilon_t^{(\tau)}, \tag{3}$$

where $Y_t^{(\tau)}$ is the vector of endogenous variables at time t and quantile τ; $c^{(\tau)}$ is the vector of quantile-specific intercepts; $A_p^{(\tau)}$ is the lagged coefficient matrices at quantile τ, and $\varepsilon_t^{(\tau)}$ is the vector of quantile-specific error terms.

3. Data and Preliminary Analysis

3.1. Data

To estimate the asymmetric risk spillovers among energy metals and clean and dirty energy markets, we sourced the weekly data of markets under study from Refinitiv Eikon from July 2014 to January 2024. The markets analyzed in the study include Crude Oil, Fuel Oil, Gas Oil, Gasoline, Natural Gas, Brent, Coal, and a range of strategic tech minerals such as Germanium, Cobalt, Vanadium, Indium, Tellurium, and Gallium. Additionally, the analysis covers eco-friendly energy markets represented by indices like the S&P Clean

Energy Index (S&P CE), Wilder Hill Clean Energy Index (Wilder Hill CE), and the Renewable Energy Industrial Index (Renixx CE).

The significance of studying strategic tech minerals and their relationship with eco-friendly and non-eco-friendly energy markets lies at the intersection of global challenges: the transition to cleaner, more sustainable energy sources, resource security, and environmental responsibility. This study holds implications for several key stakeholders, including policymakers, investors, industry participants, and environmental advocates. As the world grapples with the urgent need to mitigate climate change and reduce greenhouse gas emissions, clean energy markets have gained immense importance. Understanding the role of energy metals in facilitating this transition is crucial. These metals are fundamental to clean energy technologies, such as lithium-ion batteries for electric vehicles and renewable energy storage systems (Ugochukwu et al., 2022).

Strategic tech minerals are often concentrated in specific geographic regions, leading to concerns about resource security and geopolitical tensions. Analyzing these metals' availability and distribution can inform policymakers about potential global energy supply chain vulnerabilities to diversify sources, reduce dependence on specific countries or regions, and promote responsible sourcing practices. Investors and businesses involved in eco-friendly markets rely on accurate energy metal availability and pricing assessments. Non-eco-friendly markets, characterized by fossil fuels, have profound environmental implications. This study can highlight the stark contrast between these markets and the eco-friendly energy sector, emphasizing the importance of transitioning away from fossil fuels for environmental sustainability.

3.2. Descriptive Statistics

Figures 1, 2, and 3 provide insights into key characteristics of various markets based on descriptive statistics. The Bar Chart of mean and median values highlights general trends and central tendencies, showing the overall value levels across markets, with strategic tech minerals and certain eco-friendly indices exhibiting higher averages, indicating potential price stability or growth. The Box Plot captures the range and spread (min, median, and max) for each market, providing a clear view of data concentration and volatility; here, energy markets like crude oil and natural gas reveal a wider spread, signifying higher fluctuation, while metals like vanadium and indium show narrower ranges. Lastly, the Line Plot of the ADF Statistic values illustrates each market's stationarity, an indicator of stability over time, where markets with more negative values are considered more stable; metals generally display stronger stationarity than fossil fuel markets, which show higher vulnerability to volatility and external shocks. These visualizations underscore the diverse risk profiles and dynamic behavior across these markets, which are crucial for informed risk management and investment strategies,

Figure 1 . Mean and Median Values

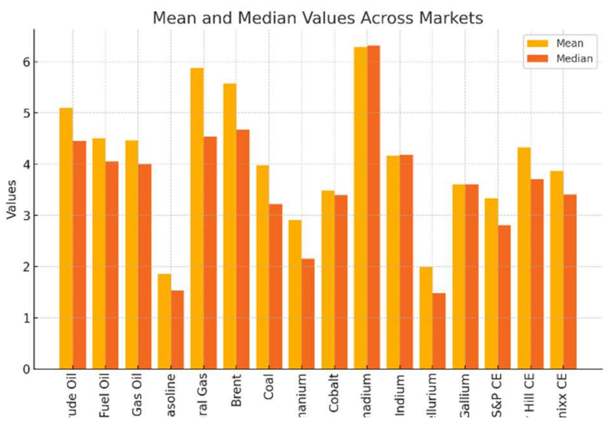


Figure 2. Box Plot of Markets

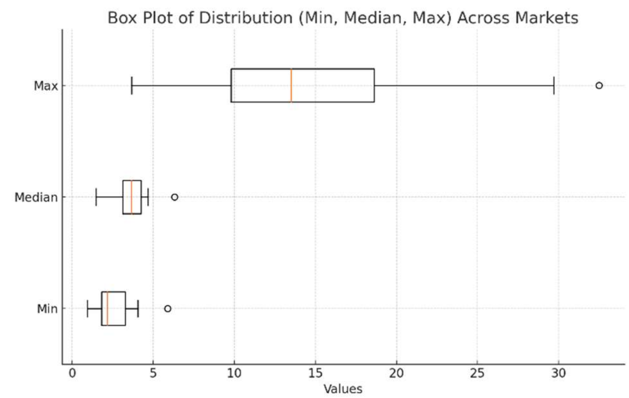


Figure 3. ADF Statistic

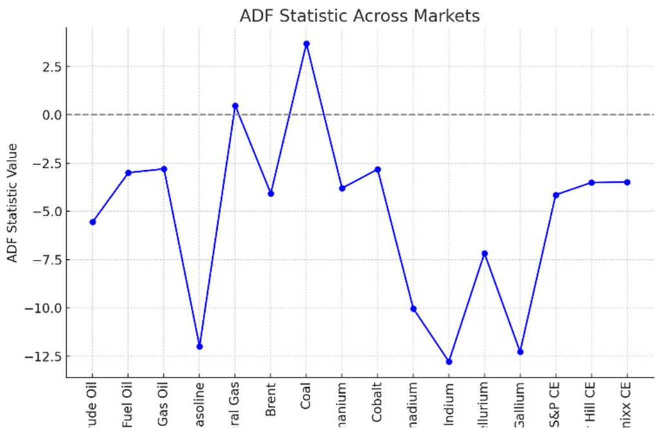
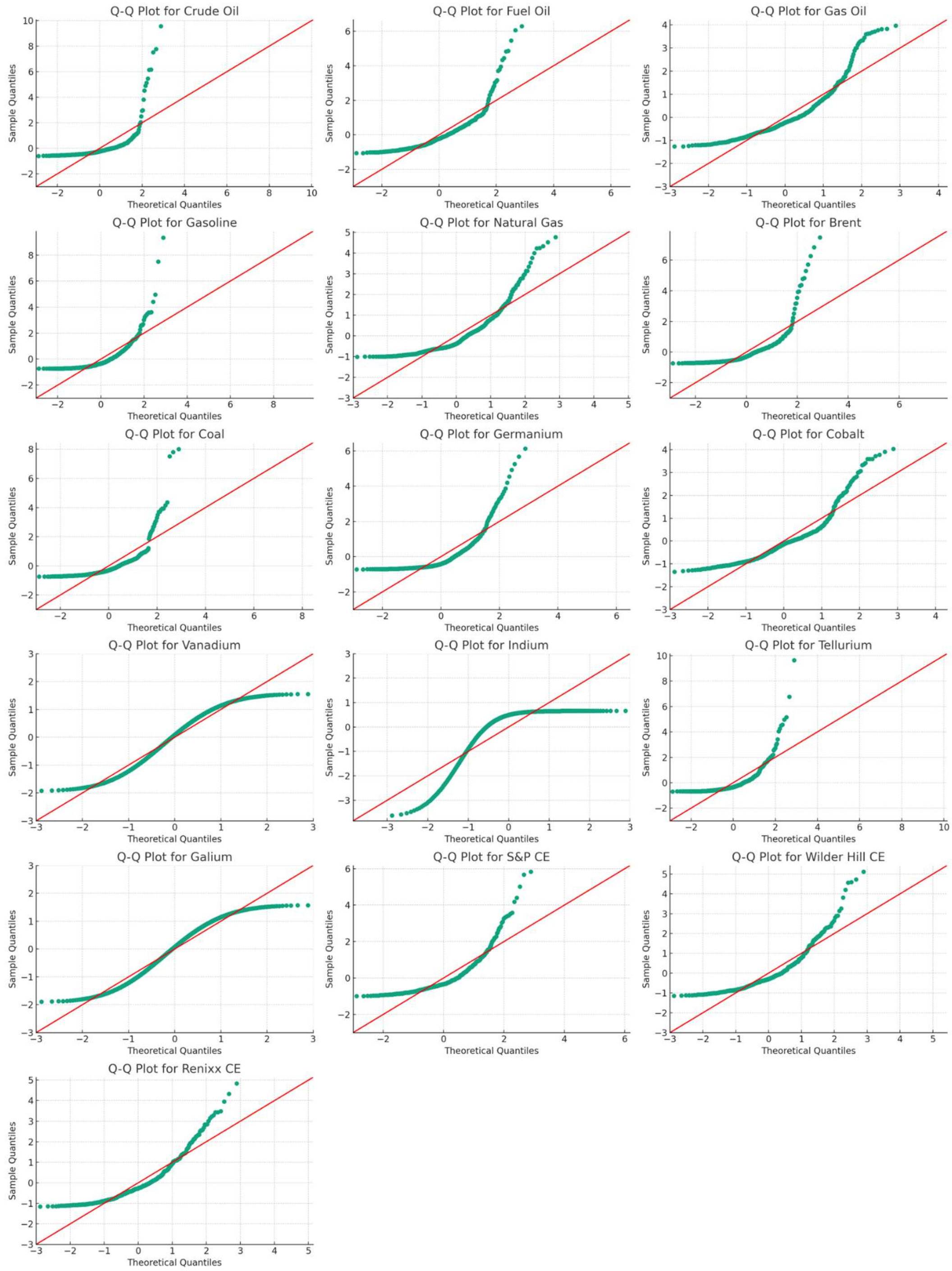


Figure 4 presents Quantile-Quantile (Q-Q) plots for various markets, including conventional energy sources, strategic tech minerals, and eco-friendly energy indices. Q-Q plots are used to compare the distribution of a dataset to a theoretical distribution, typically the normal distribution. The x-axis represents the theoretical quantiles, while the y-axis represents the sample quantiles. Points deviating from the red diagonal line indicate departures from normality.

For conventional energy markets like Crude Oil, Fuel Oil, Gas Oil, Gasoline, Natural Gas, Brent, and Coal, the Q-Q plots show significant deviations from the diagonal line, especially at the tails. This suggests that the returns of these markets are not normally distributed and exhibit fat tails, meaning they are prone to extreme values. Such non-normality can be attributed to geopolitical events, supply chain disruptions, and fluctuating demand, which can cause sharp price movements in these markets. The Q-Q plots for strategic tech minerals such as Germanium, Cobalt, Vanadium, Indium, Tellurium, and Gallium also reveal departures from normality, particularly at the extreme distribution ends. Strategic tech minerals are critical for various high-tech and green technologies, making their markets highly sensitive to supply constraints, technological advancements, and changes in regulatory policies. The presence of fat tails in these distributions indicates that extreme price movements are relatively common, reflecting the volatility and market sensitivity associated with these metals.

The Q-Q plots for eco-friendly energy indices (S&P CE, Wilder Hill CE, and Renixx CE) similarly show deviations from the normal distribution, though to varying extents. The clean energy sector is influenced by various factors, including technological innovations, government policies, and investor sentiment towards sustainability. The non-normality observed in these indices suggests that while there is growing interest and investment in clean energy, the market is still subject to significant volatility, driven by changes in policy and market perceptions of sustainability trends.

Figure 4. Q-Q Plots of Markets



The deviations from normality across all these markets reflect each sector's inherent risks and uncertainties. For non-eco-friendly markets, geopolitical tensions, environmental regulations, and shifts in global demand can lead to large price swings. Strategic tech minerals are subject to supply risks, including geopolitical issues in producing countries and the rapid pace of technological change that can alter demand patterns quickly. Eco-friendly energy markets, while benefiting from a global push towards sustainability, still face volatility due to evolving technologies and policies.

Understanding these non-normalities is crucial for investors and policymakers to develop strategies that mitigate risk and leverage opportunities in these dynamic markets. The Q-Q plots highlight the importance of considering non-linear and extreme market behaviors in financial analysis and decision-making.

4. Empirical Results

4.1. Quantile Connectedness.

Table 1 and Figure 5 comprehensively analyze quantile connectedness in the lower quantile (5th percentile), highlighting the spillover dynamics among markets during adverse conditions. The results demonstrate how each market contributes to or is influenced by others under stressed scenarios. Specifically, the "To Spillover" values capture the outgoing influence of a market on others, while the "From Spillover" values measure the incoming impact of other markets on a specific market. The "Net Spillover," calculated as the difference between "To" and "From," reveals whether a market acts as a net transmitter (positive) or receiver (negative) of shocks.

The results show that markets such as Gasoline and Tellurium emerge as significant net transmitters of shocks, with positive net spillover values of 9.56 and 20.63, respectively. This indicates their dominant role in propagating stress during adverse market conditions. Conversely, the Fuel Oil, Gas Oil, and Indium markets exhibit substantial negative net spillover values (-16.71, -11.75, and -14.51, respectively), making them net receivers of stress. These results align with the characteristics of these markets; for instance, Gasoline and Tellurium are pivotal in energy and renewable sectors, which may amplify shocks during crises. On the other hand, Indium's reliance on external supply chains may render it more vulnerable to external shocks (Diebold & Yilmaz, 2012).

The network dynamics in Figure 5 illustrate the interconnectedness among markets, with thicker edges indicating stronger spillover relationships. Notably, S&P CE and Renixx CE, representing eco-friendly indices, appear as significant net transmitters of shocks with net spillover values of 21.60 and 19.37, respectively. This highlights the increasing integration of renewable energy markets with traditional markets, even under stressed conditions. Additionally, Coal shows a strong positive net spillover (11.91), potentially due to its enduring role in energy production despite market volatility. This interconnectedness underscores the need for policymakers and investors to monitor these dynamics to closely mitigate risks during turbulent periods.

Table 1. Quantile Connectedness at Extreme Lower Quantile

Market	To Spillover (Quantile)	From Spillover (Quantile)	Net Spillover (Quantile)
Crude Oil	10.31908	10.41243	-0.09335
Fuel Oil	8.812286	25.51766	-16.7054
Gas Oil	11.33555	23.08333	-11.7478
Gasoline	27.171	17.61481	9.556188
Natural Gas	16.53851	18.50085	-1.96234
Brent	15.18791	28.10135	-12.9134
Coal	8.841226	-3.06676	11.90798
Germanium	15.60913	25.04948	-9.44035
Cobalt	15.01067	8.460704	6.549965
Indium	2.625221	17.13487	-14.5096
Tellurium	22.46294	1.834721	20.62822
Galium	-2.5092	12.14176	-14.651
S&P CE	8.295061	-13.3033	21.59834
Wilder Hill CE	17.57944	25.16466	-7.58522
Renixx CE	11.78569	-7.58207	19.36776

Figure 5. Quantile Connectedness of Markets at 0.05 Quantile

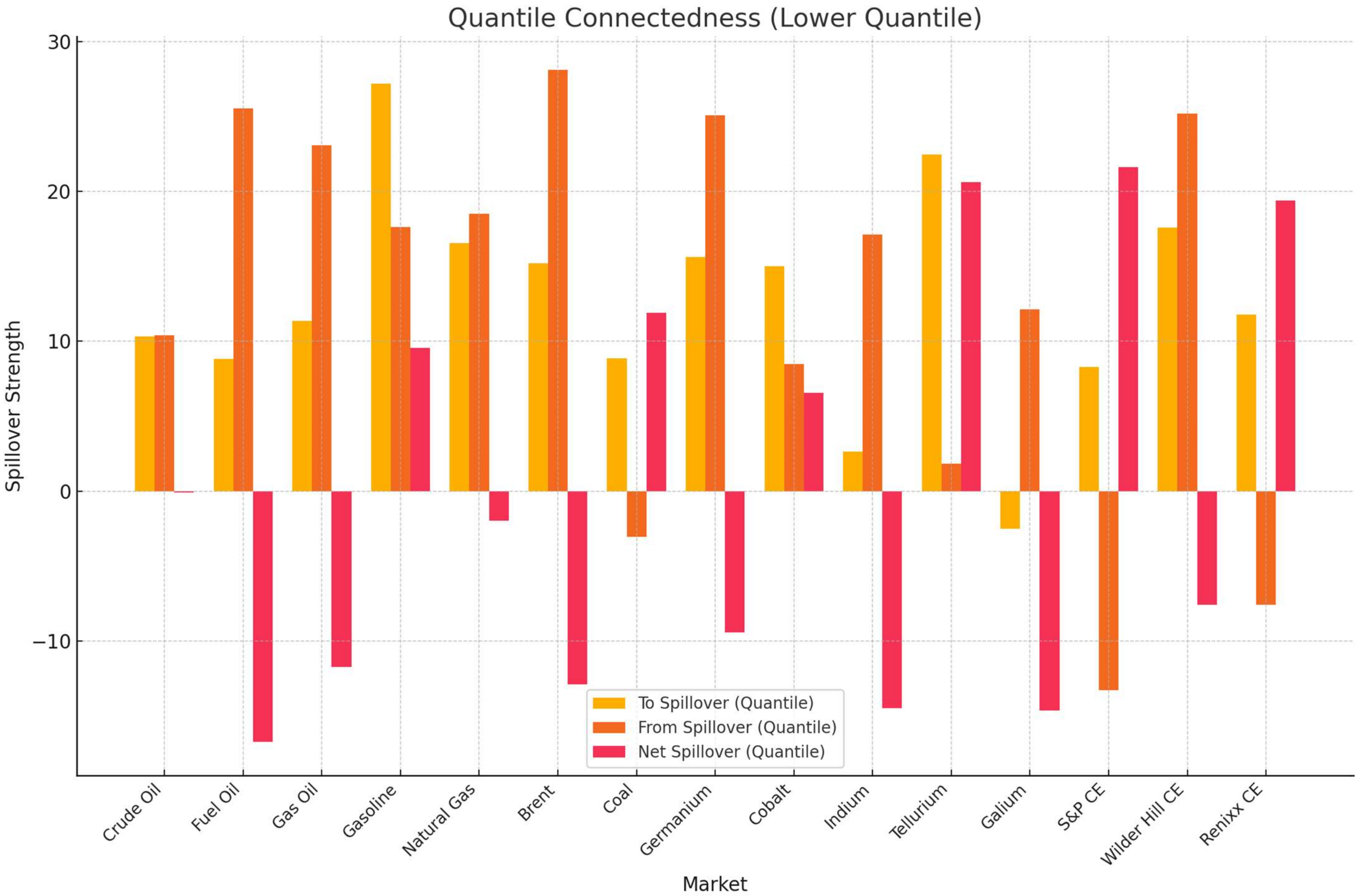


Table 2 and Figure 6 present the quantile connectedness analysis at the median quantile (50th percentile), representing the spillover dynamics under typical market conditions. In this scenario, the "To Spillover" and "From Spillover" values illustrate how markets influence or influence others during stable periods. The "Net Spillover," indicating whether a market is a net transmitter (positive) or receiver (negative) of shocks, reveals the inherent balance or imbalance in connectedness under normal conditions.

The results demonstrate significant variations in net spillovers. Gas Oil and Tellurium emerge as prominent net transmitters, with net spillover values of 72.77 and 37.03, respectively. This highlights their ability to propagate stability or shocks within the system under typical conditions, potentially due to their critical roles in energy and strategic mineral sectors. Conversely, Coal and Gasoline are substantial net receivers, with net spillover values of -93.40 and -61.16, respectively. These findings align with the structural dependence of these markets on external influences, as coal's declining demand and gasoline's price sensitivity can amplify their susceptibility to external shocks (Diebold & Yilmaz, 2012).

Figure 6 provides a visual representation of connectedness, with "To," "From," and "Net" spillovers for each market. Notable insights include Natural Gas, which transitions to a strong net transmitter (58.82), likely due to its pivotal role in energy transitions. The balance of net spillovers for indices like Wilder Hill CE (0.31) and Renixx CE (14.37) reflects the evolving integration of eco-friendly indices in global markets.

These findings highlight that Gas, Oil, and Tellurium are key transmitters of influence, reflecting their critical roles in energy and technology supply chains. At the same time, Coal and Gasoline are major receivers, likely due to their vulnerability to external shocks and demand variability. Interestingly, Natural Gas emerges as a strong transmitter, highlighting its centrality in the energy landscape during stable periods. Eco-friendly indices like Wilder Hill CE and Renixx CE exhibit balanced spillover dynamics, suggesting their integration into global markets without extreme dependence. These findings reveal a moderately interconnected system where some markets play stabilizing roles while others remain more exposed to external forces.

Table 2. Quantile Connectedness at Median Quantile

Market	To Spillover (Quantile)	From Spillover (Quantile)	Net Spillover (Quantile)
Crude Oil	53.22069	44.68387	8.536818
uel Oil	38.51384	46.9016	-8.38775
Gas Oil	80.09272	7.320655	72.77207
Gasoline	-16.4759	44.68203	-61.1579
Natural Gas	48.20162	-10.6225	58.82414
Brent	7.802112	0.013971	7.788141
Coal	0.341715	93.73903	-93.3973
Germanium	4.9316	49.9393	-45.0077
Cobalt	30.97444	50.36526	-19.3908
Indium	39.61139	22.14329	17.46811
Tellurium	93.12355	56.0954	37.02814
Galium	31.3417	11.4004	19.9413
S&P CE	5.371366	15.08009	-9.70873
Wilder Hill CE	64.42213	64.1062	0.315934
Renixx CE	11.34863	-3.02694	14.37557

Figure 6. Quantile Connectedness at 0.50 Quantile

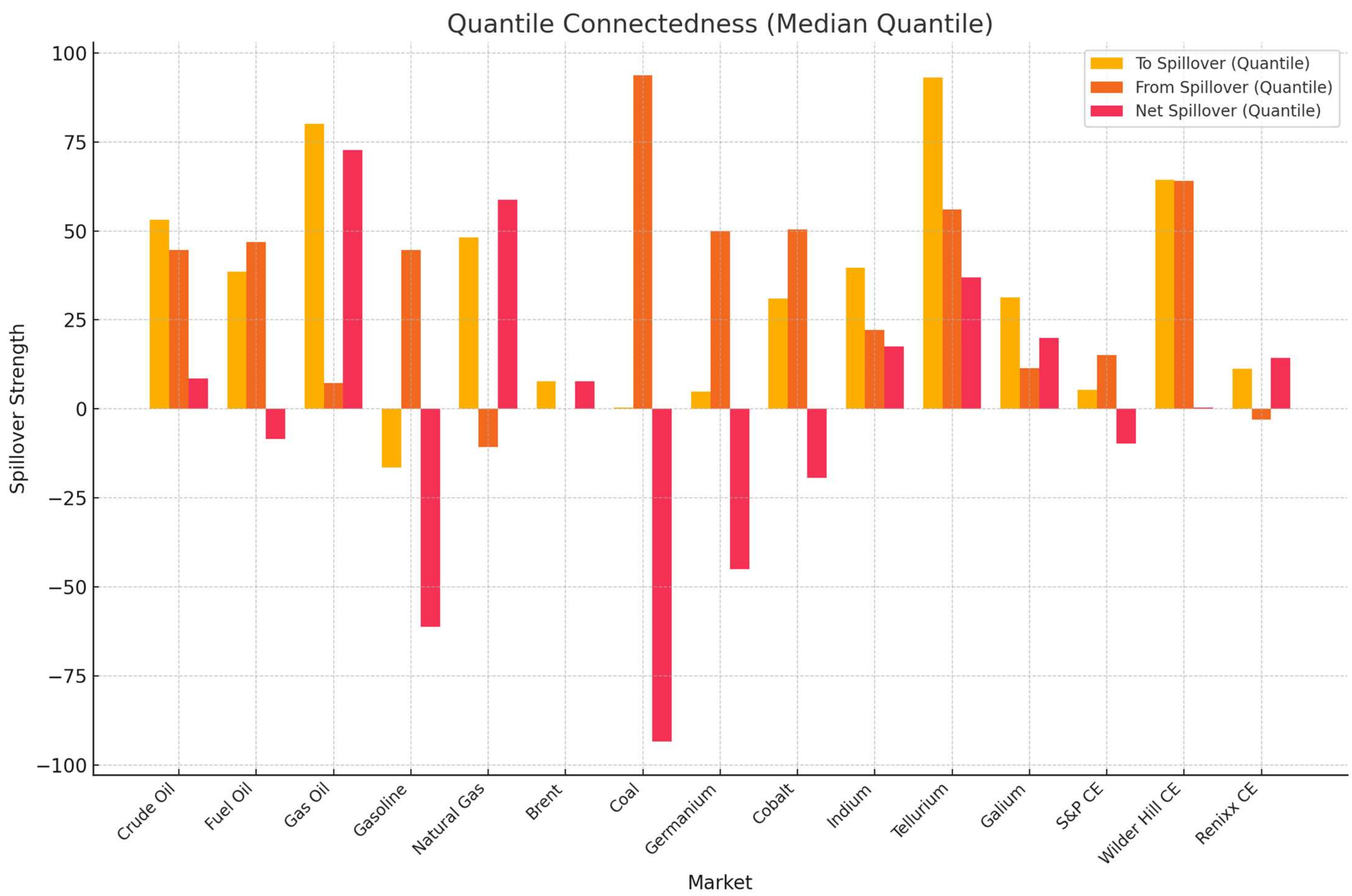


Table 3 and Figure 7 analyze market spillovers under the higher quantile (95th percentile), representing market dynamics during periods of heightened activity or extreme positive conditions. The "To Spillover" and "From Spillover" values highlight how markets contribute to or are impacted by others. At the same time, the "Net Spillover" quantifies whether a market acts as a net transmitter (positive) or receiver (negative) of shocks.

The findings reveal that markets like Coal and Gas Oil are dominant transmitters, with net spillover values of 104.88 and 95.25, respectively, reflecting their amplified influence during bullish market conditions. This dominance likely stems from their crucial roles in traditional energy sectors, often gaining prominence in high-demand periods. Conversely, Germanium, Cobalt, and Indium exhibit significant negative net spillovers (-69.45, -66.32, and -61.11, respectively), indicating their dependence on external factors and susceptibility to spillovers from other markets. Additionally, eco-friendly indices such as Wilder Hill CE emerge as influential transmitters (47.97), demonstrating their growing relevance in global financial markets.

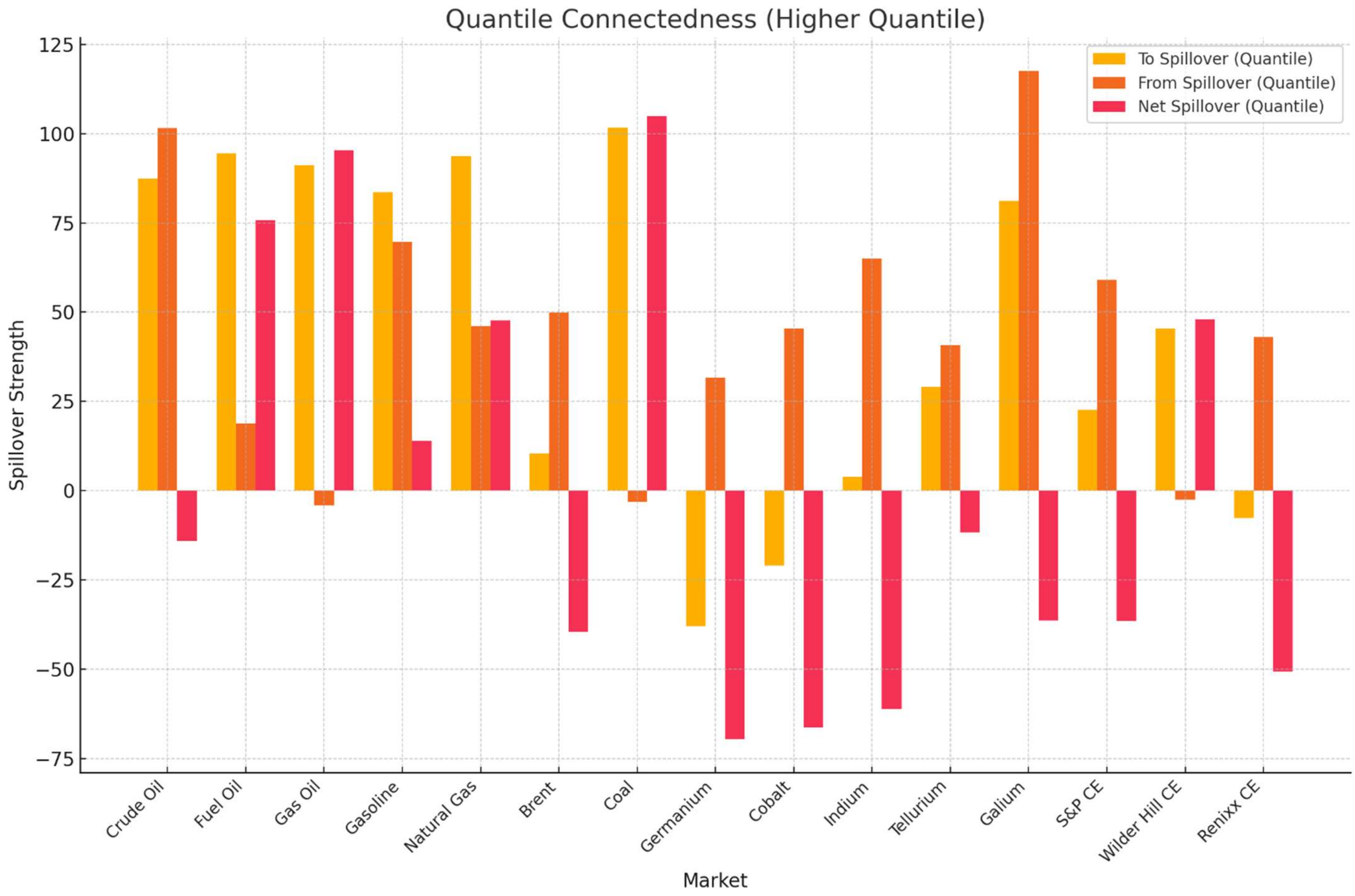
The visualization in Figure 7 illustrates these dynamics, with stronger edges representing larger spillovers. Notably, Natural Gas and Fuel Oil also act as strong transmitters with net spillover values of 47.60 and 75.74, respectively, underscoring their pivotal roles in energy transitions and industrial demand. The interconnectedness shown in the figure highlights the increased systemic risk and dependency among markets during periods of extreme market activity, emphasizing the need for robust risk management strategies during such conditions.

The findings suggest that Coal and Gas Oil emerge as dominant transmitters, reflecting their amplified influence in energy markets during high-demand periods. Germanium, Cobalt, and Indium are major receivers, showing their vulnerability to external shocks. Wilder Hill CE and Natural Gas also play significant roles as transmitters, highlighting the growing importance of renewable energy and natural gas in global markets. These results reveal an interconnected system where traditional and renewable energy markets are key drivers of systemic dynamics during bullish conditions, necessitating careful monitoring to mitigate potential cascading risks.

Table 3. Quantile Connectedness at Extreme Higher Quantile

Market	To Spillover (Quantile)	From Spillover (Quantile)	Net Spillover (Quantile)
Crude Oil	87.45947	101.4867	-14.0272
Fuel Oil	94.50938	18.7705	75.73888
Gas Oil	91.1745	-4.07435	95.24885
Gasoline	83.58188	69.58692	13.99496
Natural Gas	93.64013	46.04051	47.59962
Brent	10.46106	49.97213	-39.5111
Coal	101.7096	-3.17113	104.8808
Germanium	-37.8857	31.56679	-69.4525
Cobalt	-20.9612	45.36032	-66.3215
Indium	3.837912	64.95073	-61.1128
Tellurium	29.05176	40.73817	-11.6864
Galium	81.22198	117.5724	-36.3504
S&P CE	22.60973	59.04118	-36.4315
Wilder Hill CE	45.45376	-2.51704	47.97079
Renixx CE	-7.58607	42.95448	-50.5405

Figure 7. Quantile Connectedness at 0.95 Quantile



4.2. QVAR Estimates

Figure 8 represents the QVAR estimates of all markets included in the study. At the lower quantile, Crude Oil's significant negative coefficients indicate high vulnerability to extreme negative market shocks, which can be attributed to its critical role in the global economy. Geopolitical tensions, supply disruptions, or economic downturns can significantly impact prices, reflecting the interconnected nature of global oil markets. The moderate stability at the median quantile suggests that crude oil prices are more predictable and less volatile under normal conditions. However, at the higher quantile, the coefficients again turn negative, indicating that even during extreme positive conditions, crude oil experiences volatility and adverse effects from spillovers highlighting the market's sensitivity to global economic trends and geopolitical events (Li et al., 2022; Jebabli et al., 2022). For Fuel Oil, the significant negative coefficients at the lower quantile imply high sensitivity to negative shocks, possibly due to its dependence on crude oil prices and economic activity (Wang et al., 2019). The stable coefficients at the median quantile reflect typical market behavior, where demand and supply are balanced. However, the pronounced negative response at the higher quantile highlights that positive market conditions can still lead to volatility due to increased speculative activity or rapid shifts in industrial demand, demonstrating the market's inherent instability and the influence of broader economic factors on fuel oil prices.

Accordingly, Gas Oil shows moderate coefficients at the lower quantile, indicating some resilience to negative shocks, possibly due to its diverse industrial uses. The stable coefficients at the median quantile reflect predictable behavior under normal conditions. However, the sharp increase in volatility at the higher quantile suggests that extreme positive conditions lead to significant market reactions. These reactions could be driven by sudden increases in industrial activity or speculative trading, indicating that Gas Oil is susceptible to positive spillover effects from other energy markets during booms. Gasoline’s strong negative coefficients at the lower quantile highlight its high sensitivity to adverse market conditions, likely due to its essential role in transportation and consumer spending. The stability at the median quantile reflects its predictable nature under normal conditions. However, the extreme volatility at the higher quantile indicates susceptibility to positive market shocks resulting from fluctuations in crude oil prices, changes in consumer behavior, or policy changes affecting transportation, demonstrating Gasoline's sensitivity to broader economic and market dynamics.

Subsequently, Natural Gas’s significant negative coefficients at the lower quantile indicate vulnerability to negative shocks, possibly due to supply disruptions or economic downturns. The strong positive coefficients at the median quantile suggest stability and robust performance under normal conditions, reflecting its critical role in energy supply. At the higher quantile, the coefficients remain positive but show increased volatility, suggesting that while Natural Gas benefits from positive market conditions, it remains sensitive to market fluctuations. This could be driven by changes in industrial demand and seasonal factors, highlighting the dual nature of its market behavior. Brent oil’s strong negative coefficients at the lower quantile indicate sensitivity to negative shocks driven by global supply-demand dynamics and geopolitical factors. The moderate stability at the median quantile suggests typical market behavior with less volatility. However, the highly negative coefficients at the higher quantile reflect the volatility and sensitivity of Brent oil to extreme positive conditions influenced by global economic trends and market speculation, emphasizing the need for careful risk management in the Brent market (Su et al., 2023; Ortmann et al., 2020). Coal’s significant negative coefficients at the lower quantile highlight its sensitivity to adverse conditions driven by environmental regulations and shifts in energy consumption. The stable coefficients at the median quantile reflect typical market behavior, indicating resilience under normal conditions. However, the sharp negative response at the higher quantile indicates volatility and susceptibility to positive market conditions. This could be due to fluctuations in industrial demand and regulatory changes, underscoring the impact of broader economic factors on coal prices.

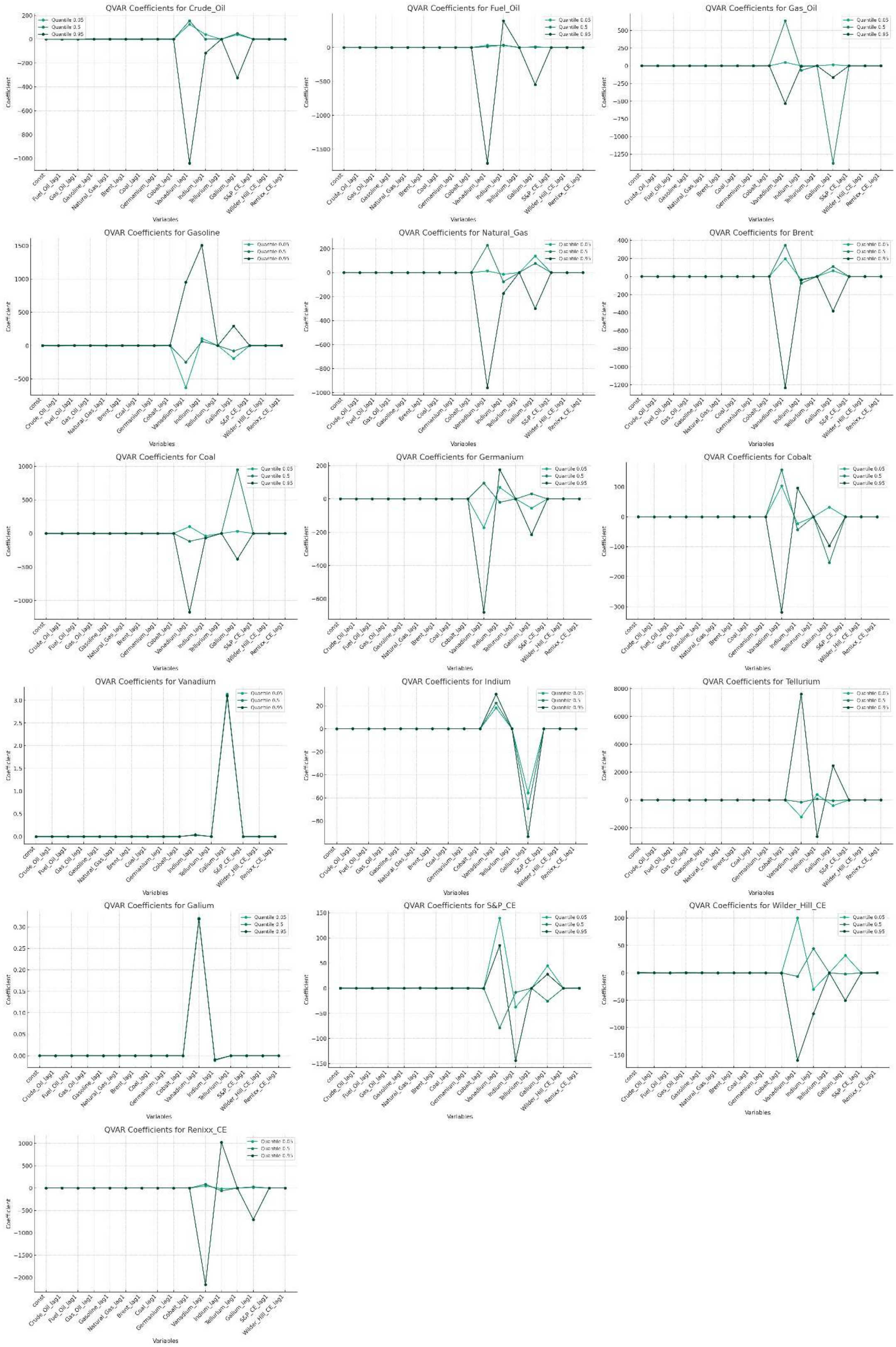
Germanium’s strong negative coefficients at the lower quantile among strategic tech minerals indicate vulnerability to negative market conditions, driven by its critical role in technology and renewable energy sectors. The stable coefficients at the median quantile suggest typical market behavior. However, the extreme volatility at the higher quantile reflects Germanium’s susceptibility to market fluctuations and positive spillover effects. This could be influenced by technological advancements and demand in high-tech industries, highlighting the strategic importance of Germanium in modern technology. Similarly, Cobalt’s significant negative coefficients at the lower quantile indicate high sensitivity to negative shocks, driven by its importance in battery technology and renewable energy sectors. The stability at the median quantile reflects resilience under normal conditions. However, the sharp negative response at the higher quantile highlights the volatility and sensitivity of Cobalt to extreme positive conditions. This could be driven by fluctuations in demand for electric vehicles and renewable energy technologies, demonstrating Cobalt's critical role in the energy transition. Contrarily, Vanadium’s minimal coefficients at the lower quantile suggest limited sensitivity to negative conditions, possibly due to stable demand in its industrial applications. The stable coefficients at the median quantile reflect typical market behavior. However, the significant spike at the higher quantile indicates heightened volatility and positive spillover effects under extreme positive conditions. This could be driven by its critical applications in energy storage and high-tech industries, highlighting Vanadium's importance in the evolving energy landscape.

Indium’s strong negative coefficients at the lower quantile indicate high sensitivity to negative market conditions, driven by its critical role in electronics and renewable energy technologies. The stable coefficients at the median quantile reflect resilience under normal conditions. However, the highly negative and volatile coefficients at the higher quantile highlight Indium's susceptibility to extreme positive conditions. This could be influenced by technological advancements and demand for high-tech applications, emphasizing Indium's strategic importance in modern technology. Tellurium's significant negative coefficients at the lower quantile indicate vulnerability to adverse market conditions, driven by its importance in solar technology and high-tech applications. The stable coefficients at the median quantile suggest typical market behavior. However, the extreme volatility at the higher quantile highlights Tellurium's sensitivity to market fluctuations and positive spillover effects. This could be influenced by technological advancements and increased demand for renewable energy technologies, underscoring Tellurium's role in the energy transition. Gallium's minimal coefficients at the lower quantile suggest limited sensitivity to negative market conditions, possibly due to stable demand in its industrial and tech applications. The stable positive coefficients at the median quantile reflect typical market behavior. However, the heightened volatility at the higher quantile indicates Gallium's sensitivity to positive market conditions and potential spillover effects. Its role in electronics and semiconductor industries could influence this, highlighting Gallium's importance in modern technology.

For eco-friendly indices, the S&P Clean Energy Index's strong negative coefficients at the lower quantile indicate high sensitivity to adverse market conditions driven by investor sentiment and policy changes. The stable negative coefficients at the median quantile reflect typical market behavior. However, the extreme volatility and negative coefficients at the higher quantile suggest that the clean energy sector experiences significant spillover effects and sensitivity to extreme positive market conditions. This could be driven by technological advancements and policy support for renewable energy, highlighting the sector's growing importance. The Wilder Hill Clean Energy Index exhibits strong negative coefficients at the lower quantile, indicating high sensitivity to negative market conditions driven by shifts in investor sentiment and regulatory changes. The stable negative coefficients at the median quantile reflect typical market behavior. However, the highly negative and volatile coefficients at the higher quantile highlight the susceptibility of the clean energy sector to market fluctuations and positive spillover effects (Shu et al., 2023). Finally, the Renixx Clean Energy Index shows significant negative coefficients at the lower quantile, indicating vulnerability to adverse market conditions driven by changes in investor sentiment and regulatory frameworks. The stable coefficients at the median quantile suggest typical market behavior. However, the highly negative and volatile coefficients at the higher quantile indicate that the renewable energy sector experiences substantial spillover effects and sensitivity to extreme positive conditions. This could be driven by global demand for renewable energy and supportive policies, highlighting the sector's critical role in the energy transition.

The analysis reveals that strategic tech minerals, eco-friendly energy indices, and non-eco-friendly energy markets exhibit varying sensitivity and interconnectedness under different market conditions. Strategic tech minerals like Germanium, Cobalt, and Indium show high vulnerability to negative shocks and substantial volatility during extreme positive conditions, reflecting their critical roles in technology and renewable energy sectors. Eco-friendly indices such as the S&P Clean Energy and Wilder Hill Clean Energy indices are highly sensitive to negative and positive market conditions, driven by investor sentiment, policy changes, and technological advancements. Non-eco-friendly markets, including Crude Oil, Fuel Oil, and Coal, display significant vulnerability to adverse conditions and considerable volatility during booms, influenced by global supply-demand dynamics, geopolitical factors, and speculative trading. Overall, the interconnectedness and sensitivity of these markets highlight the importance of strategic risk management and the need to understand the broader economic factors influencing these sectors.

Figure 8. Quantile VAR Analysis



5. Conclusion

The primary objective of this study was to analyze the connectedness and spillover dynamics among traditional energy markets, eco-friendly indices, and strategic tech minerals under varying economic conditions. Using quantile-based connectedness measures, the study focused on capturing the asymmetric spillover effects across lower (adverse conditions), median (normal conditions), and higher (boom conditions) quantiles. This approach allowed for a deeper understanding of how different market states affect the interplay between traditional and renewable energy markets and critical minerals. It provided new insights into their interconnectedness and roles in systemic risk transmission.

The results reveal substantial heterogeneity in spillover dynamics across quantiles. Traditional energy markets, such as crude oil and fuel oil, exhibit limited spillover influence in the lower quantile. Meanwhile, markets like gasoline and tellurium act as key transmitters in adverse conditions. At the median quantile, Gas Oil emerges as a significant transmitter, with eco-friendly indices showing balanced spillover dynamics, reflecting their integration into global markets. In contrast, at the higher quantile, traditional energy markets, including Coal and Gas Oil, dominate as spillover transmitters, while strategic minerals like Germanium and Cobalt act as major receivers, highlighting their dependency on external forces. These findings underscore the shifting dynamics of market interconnectedness under different market conditions.

The study employed a Quantile Vector Autoregression (QVAR) framework to capture spillover effects at different quantiles, combined with Diebold and Yilmaz's connectedness measures to quantify "To," "From," and "Net" spillovers. This methodology allowed for a granular examination of spillover dynamics while accounting for the non-linear behavior of markets under varying economic conditions. Additionally, network-based visualizations clearly depicted interconnectedness, offering both academic and practical value in interpreting the results.

The findings have significant academic and practical implications. Academically, this study contributes to the literature on connectedness by introducing a quantile-based approach, emphasizing the asymmetric nature of spillovers under different conditions. Practically, the results are valuable for policymakers and investors, highlighting the need for tailored risk management strategies. For instance, the dominance of traditional energy markets as transmitters during boom conditions calls for greater monitoring of their systemic risk. In contrast, the vulnerability of strategic minerals during adverse conditions underscores the importance of supply chain resilience. These insights are particularly relevant in energy transitions and the global push toward sustainability, where understanding the interplay between traditional and renewable markets is critical.

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