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Clean energy and the fragile supply chain: lessons from U.S.-China trade tensions and energy shocks

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Introduction: This study explores the time-varying connectedness and spillover transmission among supply chain disruptions in China, clean energy technology, energy prices (BRENT), U.S.–China trade tensions (UCT), and economic policy uncertainty (EPU). Understanding these interdependencies is crucial for assessing how shocks propagate across economic and environmental systems.
Methods: Using quarterly data from 2006 to 2024, the analysis employs the Time-Varying Parameter Vector Autoregression (TVP-VAR) and Quantile VAR (QVAR) approaches. These models capture both dynamic and distribution-dependent spillover effects across markets and policy variables.
Results: Findings indicate that Chinese supply chain disruptions act as the primary net transmitter of shocks, especially during crises such as COVID-19, trade conflict escalations, and the recent global energy shock in the Red Sea region. After 2020, climate technology emerges as a more influential transmitter in high-quantile regimes, while BRENT and UCT alternate their roles across quantiles. Robustness tests using network-based quantile analysis confirm the nonlinear and state-dependent characteristics of these spillover effects.
Discussion: The results provide new insights into how domestic disruptions in China's carbon-intensive supply chains reverberate through broader environmental, economic, and policy systems. The study offers essential implications for resilience planning, sustainable technology.

KEYWORDS

supply chain, climate-technology index, U.S.-China trade tension, EPU, Qvar

1 Introduction

With the trade war between the United States and China, continued supply chain ruptures, and energy security impoverishing the world, the fragility of the global economic systems has emerged, amplifying the urgency for clean energy transitions and resilient supply chain strategies (Allan and Nahm, 2024; Yang and Fu, 2025). We also know that the dynamics of financial markets have changed since the shift towards climate resilience and clean energy investment came into play, especially in times of high policy uncertainty and global crises, including the COVID-19 pandemic (C19P), the Russia–Ukraine conflict (RUC), and the Red Sea tension. Although previous studies have examined the mutual effects between, e.g., economic policy uncertainty and oil shocks on specific sectors, such mutual and time-varying transmission relationships among these central variables across markets remain largely understudied. To address this gap, we explore the dynamic spillover structure and quantile-dependent connectedness in five key areas U.S.-China geopolitical tension (UCT), energy (Brent), Economic Policy Uncertainty (EPU), Climate Technology (NEX), and China's supply chain (GSCH). In this study, the focus is on China-specific supply chain disruptions, which we denote as GSCH. This series reflects disruptions in China's domestic and export-related supply chain activities, and therefore differs from the Global Supply Chain Pressure Index (GSCPI), which is global in scope. These sub-domains are bridged via multiple transmission channels through which shocks in one sector matter for outcomes in the other. The first is the effect of technical and innovation spillovers, in the sense that advances (or, from another point of view, disruptions) in clean energy technology influence supply-chain efficiencies as well as input sourcing decisions and production costs; a technological shock gives rise to a shock on supply chain stress. Investment and financing connections are second in that flows of capital (e.g., foreign direct investment; green finance) can facilitate or impede the clean energy/lower carbon technology diffusion, suggesting that financial investment may slow the growth in clean energy deployment. Third, regulatory, market, and policy pathways mediate how shocks spread: trade policies, carbon pricing, and subsidy regimes can determine the influence that climate-technology shocks exert on industrial activity or supply chain stability. A third point is that nonlinear scale and composition effects mean that \(the \) size of the shock matters, as do stage of production based on economic and technological development ¾ early adopters may get significant efficiency gains from a clean energy shock. At the same time, in less developed sectors, costs may dominate initially. Using advanced econometric methods, including TVP-VAR and QVAR models, we offer strong evidence of how the shocks spill over from one area to another, particularly during extreme quantile events. The implications for policymakers, investors, and stakeholders trying to strengthen resilience in light of geopolitical, environmental, and market uncertainties are substantial.

The abnormal operations of supply chains will cause the Global Supply Chain to remain troubled for a long time. In today's international competitive business environment, the specialization of labor is becoming increasingly detailed, and the rise of outsourcing businesses and the development of economic globalization have created a longer and more complex supply chain (Baghersad and Zobel, 2021; Laguir et al., 2022). Problems caused by unpredictable events in the external environment may spread rapidly and cause GSCPI. Geopolitical conflicts, international financial crises, major natural disasters, and other black swan events will lead to GSCPI and cause serious consequences (Ali et al., 2025; Umar and Wilson, 2024; Wang et al., 2025). The supply chain has been closely embedded with economic and social life. The outbreak of C19P has caused many Global Supply Chain, which has brought severe challenges to all aspects of the basic supply chain, such as basic manufacturing, healthcare, food processing, and energy security (Parast and Subramanian, 2021). As of October 2022, C19P has not completely ended, and the RUC that occurred in February 2022 is still ongoing. Combined with adjustments in trade policies between countries, there is a high risk of disruption to supply chains. The comprehensive and far-reaching impact of C19P superimposed on RUC on lobal supply shain has not yet been revealed and needs to be further studied by the academic community (Mariotti, 2022). The resulting uncertainty is the most important and critical factor driving supply chain management (Zheng et al., 2019; El Baz and Ruel, 2021). According to a 2019 report by the Business Continuity Institute (BCI), with more than 56% of companies worldwide suffering from global supply chain issues each year, companies have begun to take global su-pply chain more seriously.

In supply chain management, the impact of CTCH factors cannot be ignored. Since the 1960s, the greenhouse effect, nuclear pollution, and extreme weather have erupted worldwide, triggering continuous public panic, social conflicts, and environmental protection movements (Streeby, 2018; Zhang et al., 2021). Any sudden environmental and climate deterioration events may cause global su-pply chain disruption, leading to potential problems affecting the national economy and people's livelihoods (Sazvar et al., 2018; Niu et al., 2022). Improving the country's environmental governance capabilities, rationally coordinating economic development, maintaining the smooth operation of various supply chains, and effectively implementing green innovation have become important dimensions of the government's administrative and modernization capabilities (Al-Maadid et al., 2025; Mohammed et al., 2025). The current circular economy, low-carbon life, climate resilience, smart supply chain, etc., all of these theories and practices involve the connection between environment, technology, economy, and transaction (Yadav et al., 2021; Zhou et al., 2020). Technological updates may lead to various ecological and environmental problems, but technological application is also one of the most important means to achieve sustainable transformation (Alkaraan et al., 2025). Technological development guarantees steady economic growth and orderly operation of supply chains. Human society's green and sustainable transformation is inseparable from the green revolution of technology (Hu et al., 2022). Similar to Climate Change Technology, policymakers need to consider EPU in managing global su-pply chain issues (Dbouk et al., 2020; Zhou et al., 2020). The government achieves the established macroeconomic goals by formulating and adjusting economic policies (Liu et al., 2021). Influenced by the characteristics of economic policies and the external environment, economic policies naturally have different degrees of uncertainty (Hou et al., 2021). The financial crisis swept the world in 2008, and

Abbreviations: CSCH, China Supply Chain Disruptions; CTCH, Climate Change Technology; EPU, Economic Policy Uncertainty; NEX, Invesco WilderHill Clean Energy; BCI, Business Continuity Institute; NOAA, National Oceanic and Atmospheric Administration; GSCPI, Global Supply Chain Pressure Index; PMI, Purchase Manager Index; SDG, Sustainable Development Goals; ICT, Information and Communication Technology; COP26, the 26th UN Climate Change Conference of the Parties; FSI, Financial Status Indicator; GPR, Gross Profit Ratio; BIC, Bayesian information criterion; TVP-VAR, Time-Varying Parameter Vector Autoregression; QVAR, Quantile Vector Autoregression.

various countries introduced economic stimulus policies to alleviate the dilemma (Peters et al., 2011). Some events in the five permanent members of the United Nations, such as Sino-US trade friction, Brexit, and RUC, have reshaped the geopolitical landscape (Proedrou, 2022). Against a complex and severe global background, global EPU presents a long-term upward trend and increased volatility (Ding et al., 2021). China's economy has entered a stage of high-quality development rather than just pursuing a growth rate. Policies to support the economy are often introduced, and the uncertainty brought about by them is an EPU issue, which has received extensive attention from scholars (Bourghelle et al., 2021; Huang et al., 2021; Zhu et al., 2021; Wang et al., 2022a). Existing literature shows that corporate capital investment decreases significantly when uncertainty about future policies rises (Gulen and Ion, 2016). Other scholars have found that when EPU rises, banks will reduce their credit supply (Valencia, 2017). EPU causes companies to be more cautious when raising funds, and it also significantly weakens the effect of loose monetary policy on investment efficiency (Bloom, 2009), hindering corporate innovation (Çolak et al., 2017; Jens, 2017). Wang et al. (2022a) found that EPU can serve as a predictor for interdisciplinary factor correlation analysis, especially under normal market conditions. EPU severely affects the energy supply chain, resulting in frequent spillovers between oil and gas resources, precious metals, and foreign exchange transactions (Ding et al., 2021).

Less academic attention has been paid to the complex relationship between supply chains, energy price volatility, and geopolitical tensions, notably those stemming from the U.S.–China trade relationship. The U.S.-China trade war has already disrupted cross-border flows of production and technology and has added to the uncertainty in both traditional and green industries. Meanwhile, prices for Brent crude oil, an internationally used benchmark for energy costs, have been highly volatile as a result of geopolitical events, OPEC + actions, and the post-pandemic recovery, with its effects on transportation costs, input prices, and the effectiveness of the adoption of clean energy. These are not independent; more and more are cross-related and time-dependent, especially in extreme market scenarios.

This paper lies at the crossroads of supply-chain shatters, energy costs, clean-energy technologies, and macro-uncertainty. While related literature studied mainly one of the two supply-chain pressures in isolation or focused on a bilateral relationship (e.g., linking policy uncertainty to oil shocks), our study encompasses these areas within an interlinked framework. Our study contributes to the literature in two primary ways. We first argue how shocks are transmitted across markets via quantile-dependent dynamics of states, and show asymmetries between low- and high-stress ranges. Second, we document a post-2020 regime change after C19P, RUC, and Red Sea energy shocks that saw strong transmission channels for supply chains, energy, and clean technology. This more extensive mapping situates our study at the intersection of supply-chain pressures research and the nascent literature on energy–uncertainty–climate interdependencies.

Based on this, from the perspective of the connectedness of supply chains, this paper examines the exogenous factors, multifaceted consequences, and corresponding internal and external management countermeasures of global su-pply chain in series to deepen and improve managers' and other relevant subjects' understanding of global su-pply chain. Also, this study investigates the connectedness among China's global supply chain, UCT, Brent, EPU, and NEX. Our analysis contributes to the literature on the interrelations between macroeconomic uncertainty, the energy markets, climate innovation, and global production systems in several important ways. To our knowledge, few studies jointly examine supply-chain pressure, energy prices, clean-energy technology, and macro-uncertainty within a unified connectedness framework. Closest predecessors include work linking uncertainty and energy/clean-tech markets (e.g., Wang Xiong et al., 2022b; Bouri et al., 2022), spillovers among climate change, technological innovation, and uncertainty (Khalfaoui et al., 2022), the role of green technologies and climate uncertainty for supply-chain performance (Cheng et al., 2023), and recent evidence on climate risk and supply-chain adaptation (Pankratz and Schiller, 2024), as well as post-COVID supply-chain transformation and policy-driven shocks (Handfield et al., 2020; Appolloni et al., 2022). Building on these strands, our incremental contribution is threefold: Firslty, we integrate the four strands, China supply-chain pressure (GSCH), Brent, EPU, and UCT—with a clean-energy index (NEX) in a single system to map cross-market propagation, particularly in the recent period, including the US-China trade tension and the energy tension in the Red Sea. Thus, by accounting for these dimensions, the analysis considers the multi-level transmission of systemic shocks, which is typically missed by standard single-market analyses. Relevance to current trends and issues, drawing from past times of crisis. The study timeframe (2006–2024) spans clinically significant global events-the financial crisis of 2008, U.S.–China trade war, C19P, URW vaccination disaster, and energy market shocks- and supports a detailed evaluation of how global systems react to acute and chronic sources of uncertainty. Secondy, while prior literature has examined the impacts of economic policy uncertainty, energy shocks, and political risk on financial markets separately, this study is the only one that integrates with environmental innovation (through clean technology indices), geopolitical conflict (by accommodating U.S.–China tension), and conventional macroeconomic fluctuation (by including EPU and Brent oil prices) for a comprehensive assessment of spillover effects during crises and normality. Thirdly, applying TVP-VAR and QVAR approaches helps us capture the time-varying and quantile-dependent nature of spillover dynamics. This two-pronged methodology allows for strong and fine-grained insights into how relationships evolve in standard or extreme market conditions. The rest of the paper is structured as follows: in section 2, after a brief literature review, we introduce the data and methods. We subsequently present empirical results, robustness checks, and policy implications, and finally, we conclude with the main results and recommendations for future research.

2 Related literature

2.1 The supply chain in a dynamic environment

Numerous papers have examined global su-pply chain in dynamic environments, with a particular focus on manufacturers, platforms, finance-related linkages, capital exports, and trade credit (e.g., Dubey et al., 2017; Öberg, 2021; Moretto and Caniato, 2021; Lin and Zhu, 2025; Liu et al., 2025). Pankratz and Schiller (2024) demonstrate that companies change the make-up of their supply chains as suppliers encounter greater climate risks, such as extreme heat or flooding. Lin and Zhu (2025) observe that diversification of supply chains enhances productivity and raises the resilience of renewable energy companies. Liu et al. (2025) stress that supply chain and inflation shocks combined with consumption shocks could hamper green technology, and digitalization increases the degree of adaptability. Agrawal et al. (2024) assert that technologies from Industry 5.0 can help alleviate climate-induced supply chain disruptions and promote sustainability. The focus is primarily on factors causing global su-pply chain rather than the potential impact of other aspects after the outage and possible measures to address the outage. As markets globalize and the operating environment becomes more dynamic, managers pursue lean supply chain management practices (Blackhurst et al., 2005; Min et al., 2019), where supply chains are optimized into more economical and responsive industrial networks. These trends present opportunities for supply chain development (Ghadge et al., 2020), placing significant pressure on a stable operating environment and increasing the risk of vulnerability and disruption (Katsaliaki et al., 2021). Global su-pply chain indicates that a company cannot meet the supply or demand required for normal operations (Hendricks and Vinod, 2005). While revealing the sudden disruption, Wilson (2007) explains global su-pply chain from the perspective of logistics and transportation. He defines global su-pply chain as events in which disruptions to logistics cause the movement of goods to stop suddenly. The global supply chain is characterized by unplanned abruptness and sudden events that can disrupt the expected flow of materials, information, and components (Skipper and Hanna, 2009; Butt, 2021).

Extreme weather, sudden disasters, and policy factors often lead to global su-pply chain. The U.S. National Oceanic and Atmospheric Administration (NOAA) has recorded 212 disasters since 1980, causing approximately $1.2 trillion in damage (Katsaliaki et al., 2021). Natural disasters such as the 2004 Indonesian tsunami and the 2011 Great East Japan Earthquake severely affected the supply chains of multiple products for companies such as Apple, Samsung, and Toyota, with the fragile chains immediately disrupted, negatively affecting the reputations and earnings of these companies (Chongvilaivan, 2012). The C19P outbreak in 2020 severely restricted factory production around the world, cut off logistics routes, and disrupted basic supply chain operations (Araz et al., 2020). Statistics from the Federal Emergency Management Agency (FEMA, 2015) show that approximately 50% of small and medium-sized businesses find it difficult to reopen after a disaster. In human factor disruptions, the risk of production failures for just-in-time carmakers and other manufacturers with similar operations has risen following Brexit (Banker, 2019). Recently, RUC has caused an imbalance in the global economic and political order, unstable energy and resource supply, blocked or interrupted supply chain networks to varying degrees, and a decline in the health index of residents (Mariotti, 2022; Malchrzak et al., 2022; Piccoli et al., 2022).

According to Luo and Kwok, 2020, C19P takes a 40% negative hit to China's supply chain. Benigno et al. (2022) developed a new barometer to measure different dimensions of GSCPI. It offers data on the United States. In addition, it embeds 27 different metrics, including logistics networks, transportation, container shipping costs, and Purchase Manager Index (PMI) surveys. Investigate the link between the environment and GSCPI using panel quantiles and document a strong association between the global su-pply chain and environmental degradation. Scholars have highlighted the problem of global su-pply chain in the literature. This topic increasingly challenges the stability of product supply chains and the efforts of core companies to consolidate their supply and demand relationships. Supply chains cross each other into networks, and chains are interdependent. Disruptions can snowball, with severe consequences for all relevant supply chain echelons. Although the Global Supply Chain Pressure Index (GSCPI) is frequently used in the literature, in this study, we rely instead on a China-specific measure (GSCH). This choice reflects the focus on China's domestic disruptions and their international spillovers.

2.2 Climate change technology and environmental challenges

In the current era of deepening globalization, informatization, and ecological processes, as well as major changes in geopolitics and international environmental politics, it is urgent to re-examine the importance of climate technology transfer in the reshaping of global su-pply chain and environmental governance, as well as its face new challenges and opportunities, and actively explore innovations in technology transfer models (Petricevic and Teece, 2019; Collins et al., 2021; Anderson, 2022). CTCH is a specific technological innovation designed to reduce the impact of product production on the natural environment, covering processes, products, services, and business management updates (Razzaq et al., 2021; Irfan et al., 2022). Information technology has made tremendous progress in the past decade and has penetrated all aspects of daily life (Guo et al., 2020). Among them, CTCH meets the needs of social progress and business development without compromising climate and natural resources (Yap et al., 2021). Research on CTCH mainly focuses on sustainable economic development, energy conservation, manufacturing technology upgrades, and their impacts on the natural environment (Shan et al., 2021; Tan et al., 2021; Li et al., 2022).

Among the observed associations between CTCH and sustainability issues in different regions, Razzaq et al. (2021) find that green innovations mitigate carbon emissions, particularly at higher emissions quantiles, by examining the asymmetric interdependence between carbon emissions and green innovation for BRICS economies from 1996 to 2017. Shan et al. (2021) consider the STIRPART model and find that innovation in climate technology plays an important role in achieving the SDG by keeping production processes on track with minimal negative impact on the environment in Turkey. Chien et al. (2021) demonstrate that information and communication technology (ICT) can help improve supply chain effectiveness and significantly reduce environmental degradation when considering the SDG framework. With the help of the bootstrap autoregressive distributed lag (BARDL) technique from 1990 to 2018, Meirun et al. (2021) believe that despite the remarkable economic growth achievements in Singapore, it still faces severe environmental-related problems, and technological innovation is an effective way to achieve environmental sustainability. In addition, many studies have explored the dynamic causal relationship between CTCH and environmental issues and have largely recognized their positive role in supply chain management, energy conservation, and emission reduction (Du et al., 2019; Jiao et al., 2020; Yang et al., 2020; Yin et al., 2020; Hao et al., 2021).

Given the uniqueness of environmental and climate issues (e.g., externalities, noncompetitiveness, transboundary, complex, temporal, and spatial heterogeneity, irreversible consequences, etc.), there is an urgent need to strategically promote and manage the invention, innovation, dissemination, and transfer of environmental technologies and use (Good et al., 2019; Gupta et al., 2021). Research on the relationship between green technology or CTCH and China's economy or supply chain is rarely mentioned. China's role is changing from a mere recipient of environmental technology transfer from developed countries to a technology supplier to other developing countries (Pandey et al., 2022). As significant emerging economies, China and developing countries face numerous challenges in economic transformation and supply chain upgrading, and they share many relevant development experiences. Learning from all parties involved and finding solutions makes CTCH critical to the effectiveness of supply chain environments.

2.3 Trade uncertainty and supply chain disruption

Recent literature emphasizes that the U.S.-China trade war has revolutionized the global supply chains through direct tax shocks and general trade policy risk. Mao and Görg (2020) show that the cumulative and indirect effects of tariffs employed during the trade war had a wide-reaching impact on bilateral trade and third parties, negatively affected by the embedded involvement in trade in global value chains. Wu et al. (2021) build on this work using the OECD Inter-Country Input-Output model to develop a methodology for quantifying the cumulative tariff impact of both direct and indirect contributions. Their results indicate that the U.S. and China bore the highest indirect costs regarding the ripple effect, with the U.S. and China incurring $10 billion and $6.5 billion, respectively. In contrast, other third-party economies such as the EU, Canada, and Mexico also had to bear significant spillover effects, which would increase by 30%–70% due to full tariff pass-through. Similarly, Benguria and Saffie (2024) also illustrate how firms re-purposed exports towards substitute destinations following tariff shocks, with the re-allocation constrained by financial conditions and prior supply linkages. Fan et al. (2022) offer firm-level evidence on how U.S. firms with deep sourcing connections to China experienced deteriorating operating performance, especially those with complex sourcing networks. Kong et al. (2024) found that the cost of innovation for Chinese firms was quite significant when facing U.S. tariff exposure. However, some strategically increased innovation so as not to fall behind. From an environmental standpoint, Yuan et al. (2023) reveal how supply chain restructuring led to an increase in emissions worldwide as production moved to carbon-intensive economies. Recent works by Padhi et al. (2024) and Tsao et al. (2024) highlight how Industry 4.0 technologies can mitigate supply chain risk under increasing global uncertainty. Similarly, as Blessley and Mudambi, (2021) observed, resilience relies on resource reconfiguration and strategic alliances, as well as, further, as Handfield et al. (2020) followed, recurring disturbances (i.e., tariffs) and permanent changes (i.e., pandemics) are speeding up the transformation of GVCs into regionalized and adaptive GVCs. These studies highlight that the U.S.–China trade war has significantly reconfigured supply chains with implications for innovation, sustainability, and resilience in global industries.

2.4 EPU on supply chain

The role of EPU in achieving the SDG, environmental governance, and supply chain resilience has been a key issue in academic research (Ali et al., 2025; Cheng et al., 2023; Kim et al., 2024). Economists have found that increased uncertainty can inhibit the flow of capital in supply chains and thus affect the normal functioning of supply chains, causing shocks.

On the one hand, EPU can cause companies to delay or cancel new supply chain network relationships that require upfront investment. Existing empirical research corroborates this statement. For example, establishing new supplier links requires start-up costs, while closing existing plants or supply chains can incur high separation costs such as severance, environmental cleanup, asset write-downs, and, in some cases, financial punishment (Cohen and Hau, 2020). In a cross-country study, Julio and Youngsuk, (2012) show that companies reduced capital expenditures and slowed the development of new markets and supply chains around elections. Based on the analysis of real options theory and the irreversibility of investment, the increase in EPU inhibits the capital output of enterprises in supply chains. This inhibitory effect is more obvious in enterprises with a higher level of investment irreversibility and a higher reliance on government spending (Gulen and Ion, 2016; Alfaro et al., 2018). Akron et al. (2020) conducted empirical research using data from companies in America's hospital industry. They found that EPU is negatively correlated with trade credit provided upstream in the supply chains of hospitals. Therefore, in response to unpredictable EPU, if companies cannot stabilize existing supply chains, they may terminate ongoing relationships and explore other supply chains (Charoenwong et al., 2022).

On the other hand, higher EPU may prompt companies to mitigate potential future shocks by expanding new relationships and building stronger supply chains, thereby preemptively reducing operational risk (Sting and Arnd, 2014; Chaturvedi and de-Albéniz, 2016). Thus, more perceived uncertainty incentivizes firms to increase the number of high-quality supplier relationships and reduce the number of low-quality suppliers, leading to disruptions in abandoned supply chains. Still, this behavior is only effective for diversifiable risks (Ang et al. al. 2017). The research of Marcus (1981) points out that in the EPU environment, it is difficult for enterprises as microeconomic entities to evaluate the benefits and risks they will face, so it is difficult to judge the impact of EPU on enterprise innovation. Some economists have found that the increase in EPU inhibits supply chains' R&D or innovation. Xu (2020) argues that the increase in EPU will increase the financing cost of enterprises, thereby reducing the overall innovation ability of the supply chains. Firms with severe financial constraints and firms that rely more on supply chain finance are more negatively impacted by EPU (Nodari, 2014; Phan et al., 2021).

Most scholars believe that the increase of EPU will significantly reduce enterprises' financing, investment, and innovation capabilities in supply chains, causing trouble in supply chain operations. From another perspective, the decline in corporate investment and innovation has impacted the supply chain, increasing the risk of global su-pply chain. As a result, EPU may affect global su-pply chain through financing, investment, and innovation channels.

Taken together, the literature indicates that these four strands, supply-chain pressures, energy prices, EPU, and U.S.–China geopolitical tensions, are not isolated but interconnected through identifiable spillover mechanisms. Supply-chain shocks (e.g., logistics disruptions, black-swan events) amplify Brent volatility through transportation and input costs, while oil price swings feed back into supply-chain stress by raising production and shipping expenses. EPU operates both directly, by altering investment flows and financing conditions, and indirectly, by magnifying volatility in oil and clean-tech markets; for instance, policy uncertainty can delay clean-energy deployment, slowing its stabilizing effect on supply chains. UCT shapes trade flows and technology transfer, disrupting both GSPCI and clean-energy innovation channels. Importantly, these channels are likely to differ by quantile regimes: in lower quantiles (tranquil states), shocks may be absorbed, whereas in higher quantiles (stress regimes), spillovers intensify and cross-domain amplification dominates. This framework motivates our empirical tests, which explicitly measure quantile-dependent connectedness among the four domains.

3 Data and methods

3.1 Data collection

This research aims to examine the connectedness of supply chain disruptions in China, considering the CTCH Index, EPU, commodity prices, and tension between the U.S. and China, using monthly data from April 2006 to April 2024. Supply-chain stress for China is proxied by the China Supply Chain Pressure Index (GSCH). GSCH follows the NY Fed methodology used for the GSCPI family and is China-specific. The Invesco WilderHill Clean Energy ETF is used in this study to track NEX as an index, which rates corporations based on their contribution to clean energy, technical influence, and climate change (Bouri et al., 2022; Wang Xiong et al., 2022b). The source of data is downloaded from the Bloomberg terminal. The following select index is the economic EPU, calculated by (Baker et al., 2022; Baker et al., 2016) as an uncertainty measure. This index is obtained from St Louis Fed Financial Stress. To measure the degree of tensions, both geopolitical and trade-related, we use the UCT (U.S.–China Tension Index) index. This index is constructed using keyword text analysis of the top five U.S. newspapers and measures bilateral tensions using the frequency and context of trade war and political conflict frames. It has been extensively used in the literature to proxy for trade policy uncertainty and geopolitical stress (Baker et al., 2016). The UCT data is pulled from the Economic Policy Uncertainty homepage maintained by the Economic Policy Uncertainty Project, which provides"searchable time-series, for analysis of the economic policy. Brent crude oil is considered in this work as a proxy for global energy and commodity market behaviour. Brent is one of the world's most widely used oil benchmarks and is the reference price for energy pricing. Energy Information Administration (EIA), a credible source of global energy data and projections. The Brent crude series can be seen as an aggregate market for energy in the sense that it summarizes and eliminates partial demand and supply-driven movements in energy prices, and it has been widely employed in fundamental empirical analysis of the relationship that exists between the commodity markets and the macroeconomic or environmental uncertainty. The data is obtained from the official website of EIA. Summary statistics of the data are shown in Table 1.

For better estimation, all data transform to return measure, which can be described as follows:

To standardize all data series and obtain consistent comparative results, we convert each variable to a return form, as expressed in Equation 1.

$$R_{it} = \ln\left(\frac{T_{it}}{T_{t-1}}\right) \tag{1}$$

Where:

T_{it}: index at time t

T_{t-1}: index at time t − 1

R_{it}: index return at the time

3.2 Definition of the method and model

3.2.1 Novel quantile connectedness

The novel quantile VAR proposed by Ando et al. (2022) is based on quantile regression and a factor structure to distinguish between common and distinctive error components. Consistent with recent applications, we employ quantile-based techniques to capture tail-dependent, state-specific spillovers and heterogeneity across market conditions (Doğan et al., 2025). This approach is widely used to quantify the connectedness in the time-frequency domain under market conditions (bearish, normal, and bullish) (Chatziantoniou et al., 2022; Cunado et al., 2022; Jain et al., 2022; Khalfaoui et al., 2022). As we compute the connectedness of Diebold and Yilmaz (2014), the mathematical representation of QVAR graphical analysis is the QVAR model used in this study is defined in Equation 2, which captures the conditional quantile dependence across variables.

$$h_t = y + \sum_{j=1}^{p} \varnothing_{j\, h_{t-1+u}} \tag{2}$$

where h_t and h_{t-1} are endogenous series vectors, y is an intercept vector error term, and $\varnothing$ depicts the parameter matrix.

The TCI, shown in Equation 3, summarizes the overall risk spillover across markets during the sample period.

$$\mathrm{TCI}_t = K^{-1}\sum_{j=0}^{k} FROM_{jt} \tag{3}$$

It measures the risk spillover over the total period. Connectedness with others is defined as:

TABLE 1 Data descriptive.

Variable	Definition	Acronym	Sources
Invesco WilderHill clean energy	CTCH -clean energy/index	*NEX*	Bloomberg terminal
Supply chain	China supply disruption/index	*CSCH*	Source: NY Benigno et al. (2022) methodology — China variant (same authors; China, U.S., Europe, and global series available) https://www.newyorkfed.org/research/policy/gscpi#
Economic policy uncertainty	calculated by (Baker et al., 2022; 2016) as an uncertainty measure/index	*EPU*	St Louis Fed/https://fred.stlouisfed.org/series/
US-China tension	Measure the U.S. china tension and trade war	*UCT*	https://www.policyuncertainty.com/
Energy prices	Represent the energy and commodities prices	*Brent*	https://eia.com/

Source: our elaboration.

The "FROM" measure, defined in Equation 4, represents the degree to which a variable receives shocks from others within the system.

$$FROM_{jt} = \sum_{i=1, i \neq 1}^{k} \phi_{jt}^{\sim}(H) \tag{4}$$

It presents the connection of each variable receiving a shock from other variables while

Conversely, the "TO" measure in Equation 5 reflects the extent to which each variable transmits shocks to others.

$$TO_{jt} = \sum_{i=1, i \neq 1}^{k} \phi_{jt}^{\sim}(H) \tag{5}$$

is the return spillover transmitter. Finally, $NET_{jt} = TO_{jt} - FROM_{jt}$ represent net directional connectedness and the difference between from and to connectedness.

3.3 Time-varying VAR (TVP-VAR) connectedness

As a sensitivity analysis of the quantile model, we also fit a time-varying parameter VAR in which the AR coefficients and shock variances can smoothly evolve. We estimate the model via a Kalman filter/smoother with discount (forgetting-factor) specification, so that recent observations receive more weight and older information is down-weighted; initialization is based on an OLS fit to the early sample, but the discount setting implies an effective memory of, say, 50 months, in line with our rolling-window reports. We calibrate the lag order and the forecast horizon as in pictures (four lags; 10-step-ahead horizon), and we update the time-dependent shock covariance with a standard exponentially-weighted updating schedule. At each time, we establish impulse-response dynamics and an order-invariant, generalized variance-decomposition to summarize the information on how much of the one-step-ahead forecast error variance in each series can be traced back to shocks in any other series. We then calculate the identical totals from, to, and net connectedness metrics as described in QVAR, but over time, paths of measures indicating evolving dynamics. Results are relatively insensitive to sensible variations in the discount rate, horizon, or lag, and they reflect regime switches identified by the quantile analysis (in particular after 2020).

TABLE 2 Descriptive statistics.

	BRENT	EPU	GSCH	NEX	UCT
Mean	0.007	0.073	0.010	0.007	−2,017
Median	0.016	0.000	0.016	0.013	−2,005
Maximum	0.598	2,141	0.726	0.315	−1,391
Minimum	−0.426	−0.619	−0.433	−0.350	−2,675
Std, Dev	0.106	0.410	0.109	0.078	0.170
Skewness	0.080	1,563	0.606	−0.489	−0.515
Kurtosis	9,230	7,298	12,950	6,027	4,749
Jarque-Bera	347,960	252,962	900,070	90,646	36,913
Probability	0.000	0.000	0.000	0.000	0.000

4 Novel QVAR results and discussion

4.1 Descriptive statistics

Table 2 shows summary statistics of all data variables. The mean for all data series is positive and close to zero except for UCT, which is 2.01, exhibiting a high return. In contrast, the SD of the EPU is higher. The series kurtosis coefficients show excessive kurtosis (with a kurtosis value of 3). The skewness values varied from zero, suggesting that the series is not symmetric. Additionally, the skewness coefficient for all series is positive except UCT, indicating that outlier data were established in recent years compared to the estimation of the early period. All series have significant results for the JB test and not normality, indicating that the series times do not follow a normal distribution.

4.2 Total connectedness of return

4.2.1 The connectedness of the total return

Figure 1 displays heatmaps with shaded and cooler hues to indicate the degree of total return connection at various quantile levels. The system is estimated based on 400 horizon forecastings and lag length BIC. The shade color indicates high contentedness, while the colder color shows lower total connectedness. The

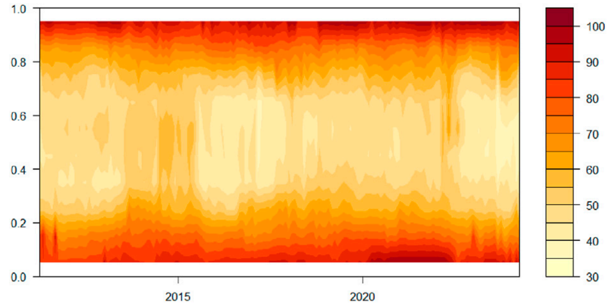

FIGURE 1
Quantile system VAR based on 50-month rolling windows, 10-variate ahead forecast, and four lags.

heatmaps show that the TCI is significantly higher at the extreme quantiles 0.05th to 0.2nd and 0.85th to 0.95th. The TCI (TCI) was higher during C19P than during RUC, at more than 80%, and 50%, respectively. Total connectedness is relatively minor at the extreme quantile of the post subprime crisis and during the European sovereign. This result is consistent with the previous studies.

4.3 The transmission spillover

This section reports the net transmission of the spillover among the supply chain, CTCH index, US-China tension, first-tramp preference, Brent, and EPU returns, as shown in Figures 2A–D. We employ a sequence of different quantiles, starting with the 5th (lowest quantile) and ending with the 95th as the highest. The warmer in this figure varies between blue (net receipt) and red (net transmit). As shown, the supply chain confirmed the outcome in The index of GSCH shows an always-present transition from being a net receiver (blue) before 2016 to a net transmitter (red) after 2017, with the net transmitters dominating in periods of significant worldwide interruptions. In particular, the C19P (2020), U.S.–China trade tensions (2018–2019), and the eruption of the RUC (2022) coincide with greater connectedness at higher quantiles (0.8–0.95). The observation suggests that (supply chain) disruptions are responding to changes on the demand side and amplifying volatility during high uncertainty. The findings report that supply chain connectedness is higher during C19P than in other periods of crisis, explained by tens of thousands of jobs being lost, production being disrupted, numerous airports and ports closing, and the cost of the shipping industry rising. This finding confirms the previous studies (Chowdhury et al., 2021; Luo and Kwok, 2020). It is also connected to domestic lockdown measures (Bonadio and Huo, 2020). Moreover, strong evidence of the connectedness between the supply chain and its determinants at extreme quantile levels highlights the need to increase countries' resilience to supply-chain-related shocks. The supply chain and climate change index are closely connected during crises and extreme quantiles. This result is consistent with Si et al. (2022), who found links between environmental degradation and the supply chain in advanced economies and emerging markets, including China. The degree of connectedness ranges between 20 and 50 at the median quantile, influenced by the quality of infrastructure associated with trade and transportation in China. It also demonstrated how logistics operations' effectiveness and quality impact China's economic success (Hong et al., 2019). Economic Policy Uncertainty acts largely as a net transmitter, especially at the upper quantiles in high-stress times (e.g., C19P, U.S.–China tension, RUC). The increase in the strength of red coloration since 2018, especially in the 0.85 quantiles and over, indicates EPU's increase of relevance in transmitting macroeconomic shocks. But before 2016 and in lower quantiles (0.1–0.3), EPU presented itself as a net receiver, implying that it seems to absorb rather than create shocks in a near-constant policy environment. UCT Index presents the latter with a more cyclical spillover structure. In the first stage of U.S.–China trade tensions (2013–2016), the index indicates that the transmission is strong at intermediate to high quantiles (between 0.4 and 0.9). This is especially the case around 2015, when President Trump was on the campaign trail and making some of his initial trade threats. A second wave of strong red clusters appeared around 2018–2019 and again during the pandemic. There is some evidence that after 2020, the index exhibits more symmetry in terms of net receiver role at lower quantiles, which agrees with the diminished independent influence of Pakistan outside the peak of geopolitical stress. The Brent crude oil price index exhibits modest and period-specific spillovers. Notably, the sudden redshift at higher quantiles circa 2014–2015 and during the 2020 oil price crash (due to C19P lockdowns and the OPEC + dispute) indicates Brent's role as a transmitter in the event of extreme market volatility. At lower quantiles and tranquil times, Brent acts more as a net receiver, responding to demand-side economic shocks instead of a source of system-wide stress. While we do not illustrate this in the present figure when examining the Climate Technology Index (e.g., NEX), it should act as a net recipient at the early stage of innovation diffusion while becoming a transmitter in recent periods, for example, green recovery agendas in the aftermath of the C19P era and response to changes in global climate policies (e.g., COP26–28). We anticipate more coupling at higher quantiles post-2020, as markets are sensitized to climate-investment signals. Since the COP26 declaration, the role of environmental CTCH, green trade, public finance for infrastructure, and supply chain management for technology and innovation has become increasingly important, in line with the SDG (Dwivedi et al., 2022). Furthermore, the direction arrow and transmission spillover from the supply chain to the technology and climate index can explain how new technologies present the need for the promising potential for improvement throughout the supply chain (Gupta et al., 2021). Blockchain technology can potentially decrease administrative expenses while increasing supply chain transparency and traceability. Based on the framework of the Sustainable Development Goals, we provide suggestions from the perspective of the CTCH, considering economic uncertainty. First, an enterprise is not just a production and manufacturing department. Managers should enhance their understanding of corporate social responsibility and quality to stay informed about policy trends while operating. Microscopic individuals can also achieve macroscopic sustainable development goals. Second, the industrial manufacturing sector may need to periodically upgrade its technology to maintain the environmental performance of its production processes. Third, policymakers should strengthen environmental regulations and legislation, and industrial production and manufacturing should be based on reducing natural resource consumption and protecting public property resources.

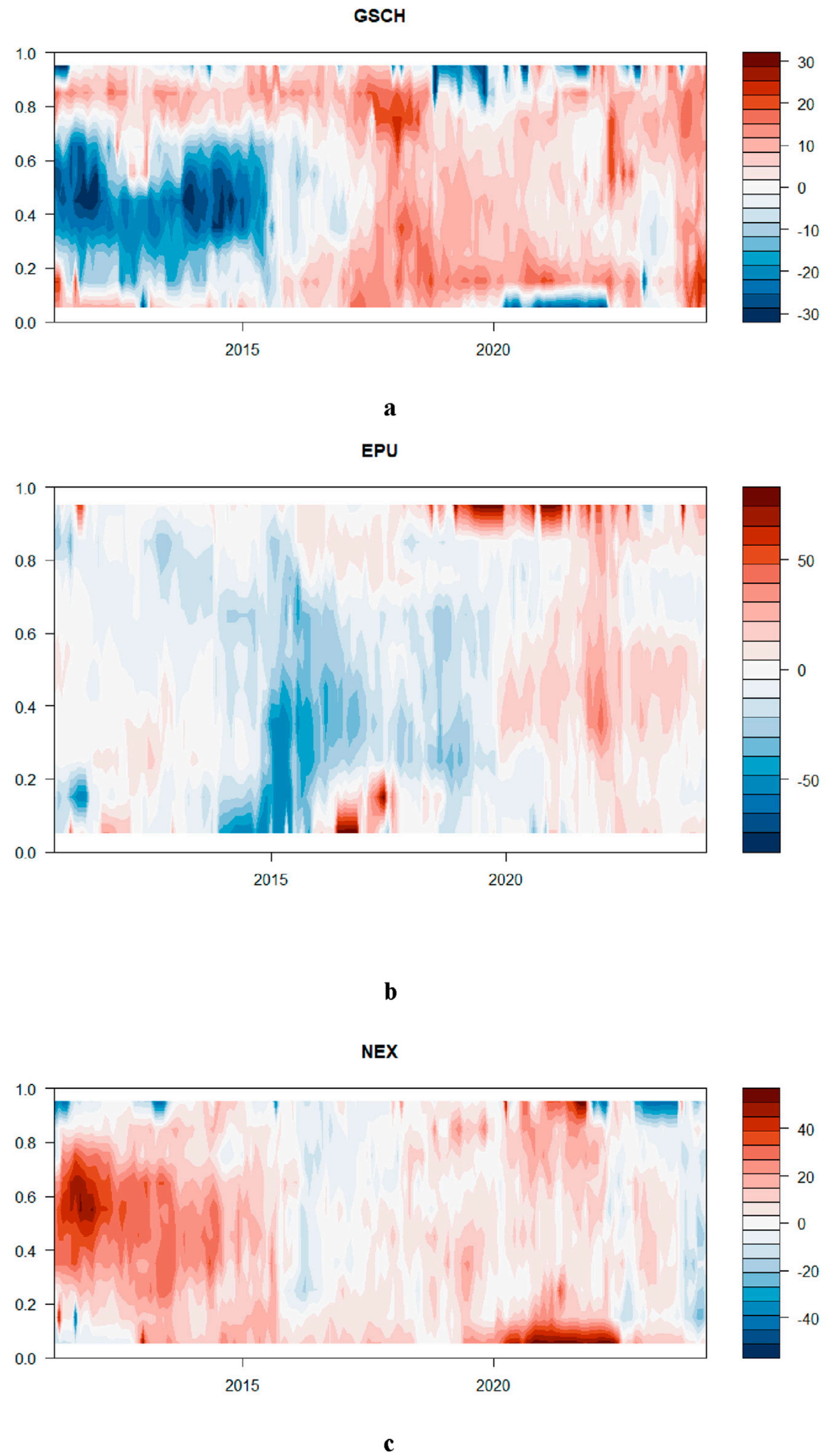

FIGURE 2
(Continued).

4.4 Robustness check

We cross-validate results from the TVP-VAR framework and a node-based Quantile VAR (QVAR) network analysis with different period rolling windows for robustness results.

Firstly, to verify our results, we apply the QVAR approach and analyze the network structure of the spillover links over a 70-month rolling window, with a forecast horizon of 20 and BIC-based automatic determination of lags. The analysis is carried out at three sample quantiles: low extreme (5th percentile), median

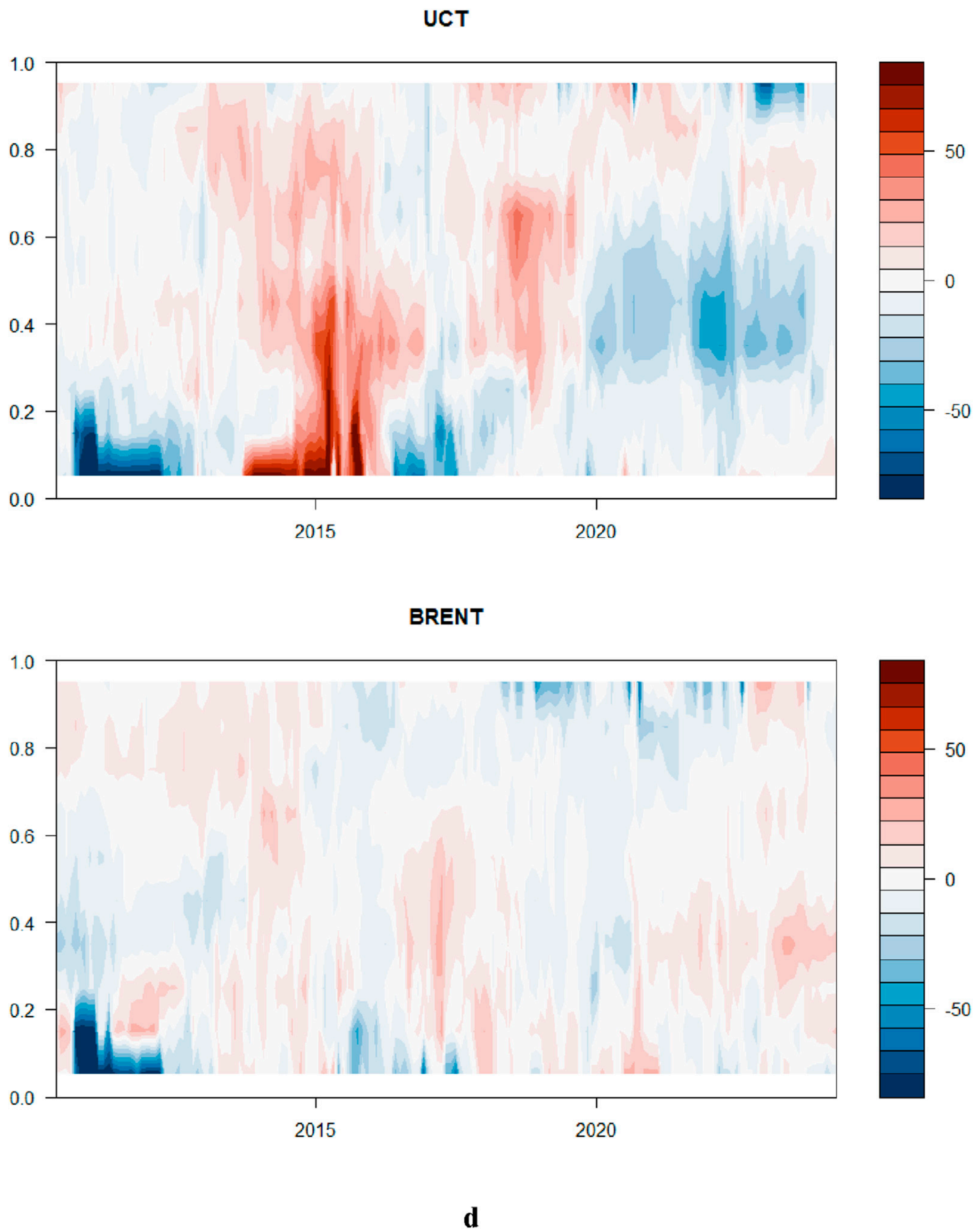

FIGURE 2
(Continued). **(a)** The total net connectedness of the supply chain return. **(b)** The total net connectedness of the EPU return. **(c)** The net total connectedness of the climate and technology index (ECO) return. **(d)** The total net connectedness of the BRENT return.

(50th percentile), and high extreme (95th percentile). The resulting networks are shown in Figure 3, with blue nodes being net transmitters of shocks and yellow nodes being net receivers. The thickness of the edge reflects the degree of directional connectedness between the variables.

In the below quantile (0.05), which seizes extreme downside conditions, GSCH and EPU show up as the main shock transmitters. At the same time, BRENT and UCT are net receivers, which means that global logistics impediments and policy ambiguity are sources of market stress in the face of adverse market conditions.

The mainstream becomes more connected at a quantile of 0.50, indicating a closer interplay between variables. GSCH and BRENT both play a relatively stronger transmitter role. At the same time, UCT and EPU are still potential shock receivers, representing the evolution from exogenous risk to even more endogenous spreading in regular market periods. On the other hand, in the upper quantile (0.95), conditioned on extremely positive outcomes, both NEX (climate tech) and BRENT become significant transmitters of dominance, signaling that the positive effects of innovative clean technology and energy markets have a

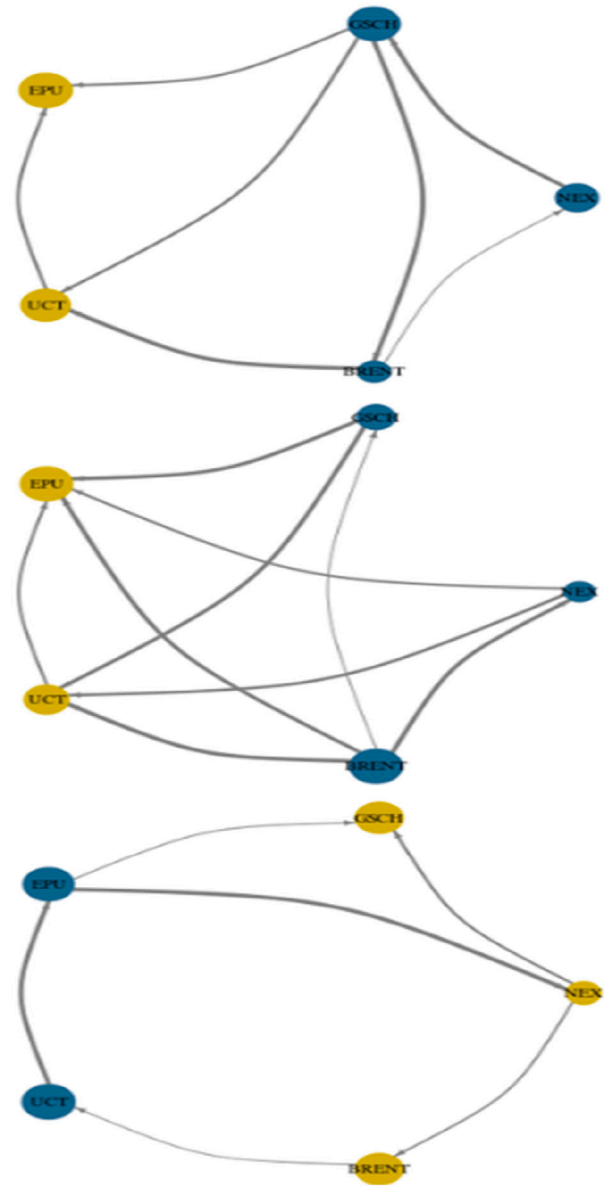

FIGURE 3
Network of return frequency-domain spillover at the 0.95th quantile.

more substantial amplifying impact on the system. On the other hand, GSCH, EPU, and UCT become net recipients again, illustrating their passive reaction to favorable market conditions. The frequency-specific network results corroborate the nonlinear and asymmetric characteristics of systemic risk transmission among climate, energy, supply chain, and geopolitical aspects. The diversity of node roles in quantiles also adds evidence to the robustness of the quantile-based connectedness framework to capture heterogeneous spillover properties in different market states.

Secondly, Figure 4 shows the time-varying net pairwise connectedness between five essential variables, which are NEX, UCT, SCH, Brent crude oil, and EPU, under the -VAR model with a 50-month rolling window, 10-step-ahead forecast horizon, and four lags. A positive value of the impact index means the variable is a net transmitter of shocks, whereas a negative value signifies a net receiver. The findings demonstrate significant heterogeneity in transmission dynamics across time. The NEX index was in net receiving countrydom until 2020, when it became a strong net transmitter, when the world entered a new phase of post-pandemic recovery and increasing global climate action, notably with the COP26 summit. This change represents an increasing power of green technologies to generate systemic market spillovers. In comparison, the unithank index in the U.S.–China trade war period (2013–2019) exhibited a significant net transmission, which indicates an increase in the couple's relationship problems. However, UCT reverted to a net receiver after 2020, meaning its effect became attenuated in the context of wider geopolitical and macroeconomic upheavals. There were variations throughout time for the GSCH index, which, after 2018, became a net transmitter (especially after the C19P and the related supply chain disruptions) and served as an intermediary for the diffusion of economic shocks. Brent oil prices, in sharp contrast, averaged near neutrality or, at most, a marginal net receiver over the whole period, with only short periods of net transmission coinciding with major oil market shocks in 2008, 2014, and 2020. Third, the contagion effect of the EPU index has transformed from a beneficiary in previous years (2000–2007), to a majority gainer since 2008, and significantly peaked during the C19P crisis, the RUC, and energy tension, demonstrating an increasing systemic impact of economic policy uncertainty in stormy periods. Overall, the resulting network maps four are consistent with the dynamics of the identified dynamic spillover roles from the TVP-VAR-based net PW connectedness. In sum, the consistency of findings on these two different but complementary approaches, TVP-VAR and quantile-based network analysis, offers strong empirical support for the robustness, nonlinear, and quantile-dependent spillover structures, guaranteeing the reliability and robustness of our main results.

5 Conclusion and implications

This paper attempts to provide a comprehensive overview of existing research, integrate GSCH, CTCH, uncertainty trade, energy, and EPU into a unified framework, and systematically analyze the impact and transmission mechanism theoretically. Results indicate a strong connection between GSCH, CTCH index, US-China trade tension, Brent and EPU, and the spread of C19P. Additionally, the Russia-Ukraine conflict, the read sea energy shock, and China-US trade tensions significantly influence the connectedness frequencies. Our findings contribute to the literature and have several implications for theory and practice. The results provide researchers with key information about what can be considered fundamental work in this area.

We believe this paper's findings may guide policymakers and industry researchers in management decision-making and crisis management. Based on the innovative data analysis in this article, we provide managers with practical guidance on five areas

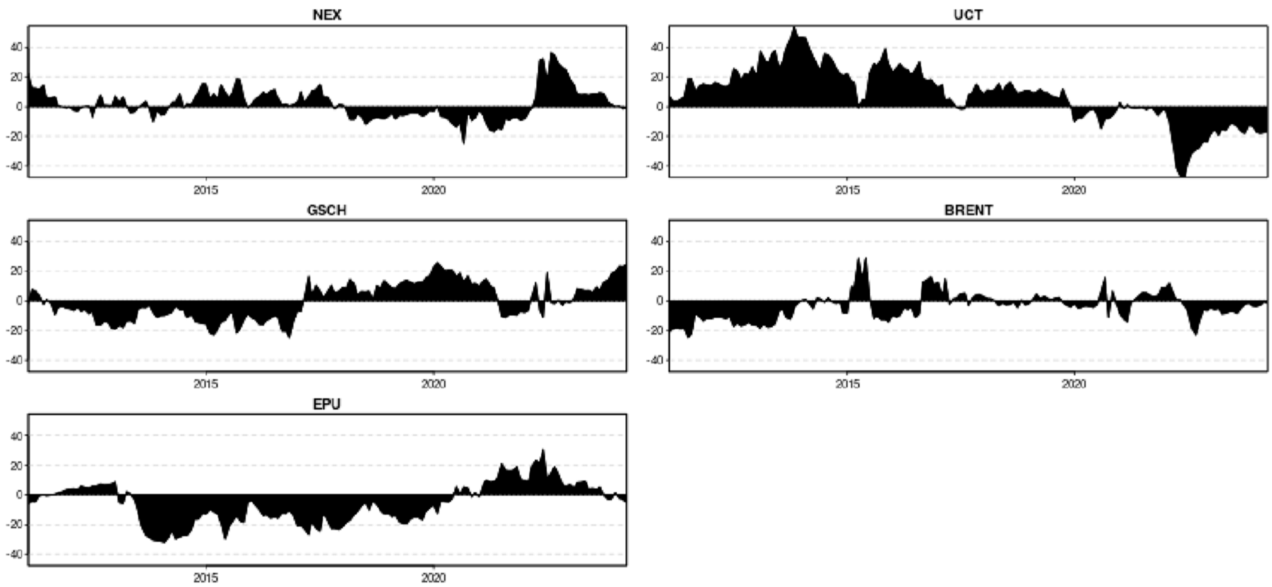

FIGURE 4
Net pairwise connectedness on the return.

to promote the connectedness of GSCH, CTCH, energy prices, trade uncertainty, and EPU. First, this study can help practitioners (e.g., presidents, COOs) to shift their corporate development focus to technological advancements in their organizations, and the findings of this study can be used to understand how CTCH, EPU, and US-China trade tension intersect across sectors and management domains for optimal management. Second, the findings reveal how the impact of CTCH, which is associated with GSCH, is considered in supply chain management. Third, in the process of supply chain operation, EPU will have a greater impact, and practitioners should predict in advance and properly handle it afterward. Therefore, this study calls for the attention of organizational decision-makers and professionals in operations management, logistics, and information technology to consider these factors.

Similar to previous studies, our study has some limitations, which provide opportunities for future research. First, we collect data at a point in time. The study has a cross-sectional design, and we do not have the longitudinal data needed to investigate causality over time. Therefore, in the long run, longitudinal studies may provide useful insights into the interplay between GSCH, climate technology, and EPU. Second, our study mainly examines GSCH, CTCH, and EPU in China, and future studies in other countries may provide new and interesting conclusions. Finally, future research could investigate measures to prevent disruptions and consolidate supply chains. Further research may examine how other information processing and technology levels affect GSCH. Finally, we believe that industry practitioners may benefit from utilizing the innovative research method of this paper to delineate the various fine-grained research frontiers related to the specific components of supply chains in different management domains, such as technology research and development, transportation efficiency, and data storage.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KM: Data curation, Software, Writing – original draft. RM: Formal Analysis, Conceptualization, Writing – original draft. SB: Software, Writing – review and editing, Visualization, Methodology. LP: Visualization, Investigation, Supervision, Writing – review and editing. MB: Funding acquisition, Conceptualization, Writing – review and editing, Resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer JC declared a past co-authorship with the author KSM to the handling editor.

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