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Critical minerals volatility under ESG uncertainty: Implications for the clean energy transition

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ABSTRACT

Critical minerals are essential to the clean energy transition as key inputs for renewable energy technologies. However, growing uncertainty in environmental, social, and governance (ESG) factors has introduced significant volatility into critical mineral markets, with implications for energy security and sustainability. This study investigates the impact of ESG uncertainty (ESGU) on the volatility of critical minerals using global monthly data from November 2002 to September 2024 and applying quantile-on-quantile regression (QQR) techniques. The results reveal heterogeneous relationships across the distributions: ESGU is negatively associated with critical mineral volatility at lower ESGU quantiles and higher mineral quantiles (except platinum); neutral associations emerge at mid-quantiles; and strong positive associations are observed when both ESGU and mineral volatility are high. These findings highlight how ESG-related risks add layers of unpredictability to mineral markets, potentially affecting clean energy production costs, investment flows, and long-term supply chain resilience. Policymakers should mitigate these risks by diversifying supply chains through domestic exploration, international partnerships, and strategic stockpiling to ensure stable access to critical raw materials for the clean energy sector.

1. Introduction

The global transition toward clean energy has intensified the demand for critical minerals, such as copper, zinc, platinum, lead, silver, and nickel, which are essential for renewable energy technologies, battery storage, and electric vehicle production. Copper is crucial for electrical wiring and grid infrastructure due to its high conductivity, while zinc is extensively used for battery production and galvanization to prevent corrosion (Calderon et al., 2024; Reich and Simon, 2024). Platinum plays a vital role in hydrogen fuel cells, an emerging clean energy technology, while lead is a key component in lead-acid batteries, which remain important for backup power systems (Zeng and Zhang, 2010). Silver's superior conductivity makes it indispensable in solar panel manufacturing, and nickel is a fundamental element in lithium-ion batteries, enhancing their energy density and stability (Peters et al., 2017). The diverse roles of these minerals highlight their importance in enabling a sustainable energy future and underline the urgency of understanding the factors influencing their market stability.

The clean energy transition is projected to drive a significant increase in mineral consumption, with the International Energy Agency (IEA) estimating that demand for critical minerals could quadruple by 2040 (IEA, 2021). This shift has amplified the volatility of these minerals, influenced by supply chain dynamics, geopolitical uncertainties, and emerging regulatory policies (Humphreys, 2010). At the same time, Environmental, Social, and Governance (ESG) considerations have become central to investment decisions, shaping market expectations and regulatory frameworks (Giese et al., 2019). ESG-related uncertainty has introduced additional layers of risk and unpredictability into mineral markets, influencing production costs, investment flows, and long-term supply chain sustainability (Broadstock et al., 2021; Shah et al., 2024). According to the ESG-Related Uncertainty Index created by Ongan et al. (2025), global ESG uncertainty has seen significant fluctuations, with peaks during financial crises and regulatory shifts, highlighting the need to examine its impact on commodity markets. Despite

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the growing relevance of ESG factors, their impact on the volatility of critical minerals remains underexplored. Previous research has largely focused on the macroeconomic and geopolitical determinants of mineral price fluctuations, often overlooking the role of ESG uncertainty in shaping market volatility (Islam et al., 2024; Saadaoui et al., 2025; Shah et al., 2023; Zhang et al., 2025). Studies examining ESG frameworks tend to emphasize corporate governance and sustainability reporting rather than their influence on commodity markets (Tilton, 1996; Alnafrah, 2024). This gap necessitates an empirical investigation into the interconnected forces shaping mineral markets, particularly through the lens of ESG uncertainty. This study uniquely addresses these gaps by integrating a refined measure of ESG-related uncertainty and employing advanced volatility modeling techniques to uncover its dynamic effects on critical minerals.

To strengthen the conceptual foundations of this study, the interaction between ESG uncertainty and commodity markets can be understood through an integrated lens of *resource curse theory* and *financial risk theory*. ESG uncertainty embodies regulatory, reputational, and compliance risks that influence investor sentiment, operational costs, and long-term market expectations. These dynamics can trigger price instability, especially in mineral markets where environmental and governance challenges are deeply intertwined with extraction and trade processes. ESG shocks—such as abrupt changes in sustainability standards or social unrest—can disrupt supply chains, affect capital allocation, and intensify speculative trading behavior, all of which increase market volatility. Moreover, based on financial risk theory, ESG-driven events often cluster in time, compounding volatility in a non-linear and asymmetric manner. This study hypothesizes that higher ESG uncertainty amplifies critical mineral volatility by introducing information asymmetry, raising risk premiums, and destabilizing investment cycles. These theoretical insights not only guide the choice of non-linear, quantile-based estimators but also inform the empirical hypotheses explored in the subsequent sections.

The volatility of critical minerals presents challenges for stakeholders, including policymakers, investors, and manufacturers reliant on stable mineral supplies for clean energy technologies. Historical data indicate that the volatility of critical minerals, as measured by the MF2-GARCH model, has exhibited significant fluctuations over time. For instance, nickel volatility (NICV) has shown peaks of up to 0.775, while copper volatility (COPV) has ranged from 0.070 to 0.841, emphasizing the instability in mineral markets. While existing studies have examined macroeconomic and geopolitical determinants of mineral price fluctuations, limited attention has been given to the role of ESG uncertainty as a key driver of volatility (Jacks and Stuermer, 2020). ESG uncertainty influences regulatory stringency, corporate governance policies, and environmental compliance costs, all of which can impact mineral supply and market stability (Li and Polychronopoulos, 2020). Given the increasing regulatory focus on sustainable business practices and the intensification of green finance initiatives, understanding the intricate relationships between ESG uncertainty and mineral volatility is vital. This study, therefore, seeks to bridge the existing knowledge gap by providing a rigorous empirical assessment of how ESG uncertainty influences the stability of critical mineral markets and the broader implications for the clean energy transition.

This study contributes to the emerging literature by introducing ESG-related uncertainty as a critical, yet previously underexplored, driver of volatility in mineral markets essential to the clean energy transition. By integrating a global GDP-weighted ESG Uncertainty Index, the study provides a refined and policy-relevant measure of sustainability-induced risk. Methodologically, the study advances empirical inquiry by combining MF2-GARCH models with time-varying correlation analysis and quantile-on-quantile regression. These approaches capture the nonlinear and asymmetric effects of ESG uncertainty across different levels of mineral market volatility. To ensure robustness, alternative volatility estimators such as the GAS-GARCH Student T model are also applied. These methodological innovations offer deeper insights for both academic researchers and practitioners seeking to understand and manage ESG-driven risks in the energy and mineral sectors. The findings have important implications for energy security, investment behavior, and sustainable supply chain planning, thereby supporting more resilient pathways toward global decarbonization.

Second, it employs the MF2-GARCH model, a robust approach for estimating volatility dynamics, ensuring a precise understanding of market fluctuations (Engle, 2002). The study further advances the methodological frontier by integrating time-varying correlation analysis, which allows for an assessment of how the relationship between ESG uncertainty and mineral volatility evolves over time, offering deeper insights into the shifting nature of market risk. Additionally, it employs advanced econometric techniques, such as Quantile Causality and Quantile-on-Quantile Regression, to capture nonlinear dependencies and asymmetric effects, highlighting the differential impacts of ESG uncertainty across varying market conditions. The robustness of these findings is reinforced through alternative volatility estimations, including GAS-GARCH Student T Volatility, demonstrating the consistency of the results across different methodological approaches.

The findings of this study have significant implications for both academic research and policy formulation. For instance, they underscore the necessity of stable and predictable ESG regulatory frameworks to minimize market volatility. Policymakers could use these insights to design targeted strategies, such as establishing ESG compliance incentives or stabilizing mineral supply chains through risk mitigation policies. Additionally, financial institutions and investment bodies could develop risk assessment models that integrate ESG uncertainty measures, helping investors make informed decisions. By highlighting these policy dimensions, this study contributes to a more structured approach to managing the intersection of ESG considerations and critical mineral markets. For researchers, the study advances the understanding of ESG uncertainty as a financial risk factor affecting commodity markets, particularly in the context of the clean energy transition.

It also provides methodological insights by applying state-of-the-art volatility modeling techniques to critically assess risk dynamics in mineral markets. For policymakers, the study offers critical insights into how ESG regulations and uncertainty can influence mineral supply stability and price volatility. For example, the study finds that periods of heightened ESG uncertainty coincide with increased volatility in critical mineral markets, underscoring the need for stable and predictable regulatory frameworks. These insights are instrumental in formulating policy frameworks aimed at balancing environmental sustainability goals with market stability. Furthermore, the study provides valuable information for investors and industry stakeholders seeking to navigate ESG risks and develop strategies for mitigating exposure to mineral market fluctuations. The ability to anticipate ESG-driven risks can facilitate more informed decision-making in capital allocation, ensuring that investment strategies align with both financial and sustainability goals. By addressing these critical issues, the study contributes to more resilient and sustainable clean energy supply chains, ensuring a stable and reliable flow of critical minerals essential for the global clean energy transition.

The remainder of this study is structured as follows. Section 2 provides a review of the relevant literature, examining existing studies on ESG uncertainty and mineral volatility. Section 3 outlines the data sources and methodological framework employed in this study, detailing the estimation techniques used to analyze the impact of ESG uncertainty. Section 4 presents the empirical results and discussion, highlighting key findings and their implications. Finally, Section 5 concludes with a summary of key insights and provides policy recommendations for enhancing stability in critical mineral markets amid growing ESG concerns.

2. Literature

2.1. Theoretical underpinnings

The resource curse theory serves as the central theoretical framework in this study, suggesting that the extraction of valuable resources in late-developing countries can foster administrative inefficiencies and political instability, ultimately contributing to economic volatility (Imran et al., 2024). This theory argues that resource wealth may diminish the incentive for leaders to establish strong bureaucratic institutions, leading to governance challenges and exacerbating price fluctuations through ESG-related concerns (Smith, 2007). Moreover, the scale and volatility of resource revenues are frequently linked to heightened bad governance, all of which hinder sustainable economic growth (including the transition to cleaner energy) and compromise public welfare (Hammond, 2011). On the other hand, financial risk theories suggest that the relationship between ESG uncertainty and mineral price volatility can be effectively explained through the lens of ARCH/GARCH models, which emphasize volatility clustering (Engle, 1982; Bollerslev, 1986). These assumptions are based on the premise that prolonged price fluctuations due to uncertain market conditions can be analyzed through volatility clustering and investor behavior influenced by ESG criteria (Zheng et al., 2023). Additionally, market instability may be amplified by sudden capital flows, reflecting ESG-driven investor behavior, and increased downside risk and market volatility can result from economic policy uncertainty (Jin, 2024). Furthermore, negative ESG incidents have been associated with heightened implied volatility in stock options, as explained by geopolitical risks (Tang et al., 2025). This phenomenon arises when uncertain market conditions, including changes in ESG regulations and supply chain vulnerabilities, result in sustained price fluctuations (Orpiszewski et al., 2024).

Intuitively, the clean energy transition is influenced by both the resource curse and financial risk theories, as governance challenges and ESG uncertainty shape economic and energy policies targeting transition to clean energy. Additionally, ESG-driven financial volatility affects critical minerals like lithium and cobalt, essential for renewable technologies. Investor responses to environmental policies contribute to market instability, raising costs and increasing uncertainty in the transition to clean energy.

On the empirical front, debate on minerals volatility, ESG uncertainty and its implication on clean energy transition are divided into various segments as thus: (i) Mineral Volatility and Clean Energy Sector (ii) ESG uncertainty and Clean Energy Sector.

2.2. Mineral volatility on clean energy sector

The volatility of mineral prices is essential in the clean energy sector, affecting both the supply chain and financial markets and are indispensable for the production of renewable energy technology. For example, Geopolitical tensions originated from Russia-Ukraine conflict, have demonstrated the capacity to destabilise mineral markets, hence generating ripple effects within the clean energy sector. This volatility can elevate expenses and heighten uncertainty for clean energy initiatives, thereby hindering the transition to sustainable energy sources (Pata et al., 2024a). Chen et al. (2024) found that Geopolitical Risk (GPR) and Economic Policy Uncertainty (EPU) affect market conditions in distinct ways. Although EPU positively influences clean energy stocks over the long term, it adversely impacts both clean and conventional energy sectors in the short term; conversely, GPR continuously applies downward pressure on conventional energy equities. Pata et al. (2024b) analyze the impact of Environmental Policy Stringency (EPS) and Energy Policy Uncertainty (ENPU) on renewable energy minerals in Russia and found that while EPS promotes the extraction of renewable energy minerals, ENPU hinders resource extraction, potentially disrupting the supply chain for renewable energy production. Using volatility connectedness, Coskun et al. (2023) found that geopolitical risks and global crises have high intensity to influence clean energy stocks. Mariev and Islam (2025) align with this outcome by showing that these factors create supply uncertainties, which in turn disrupt the steady flow of renewable energy resources and investment strategies, creating ripple effects on the clean energy industry.

Using the commodity market volatility for example (VUXXLE index), Dutta et al. (2020) found that periods of high volatility in the energy sector affect investors' sentiments which in turn have a significant negative impact on clean energy asset returns. Goutte and Mhadhbi (2024) also confirm that volatility in metal prices can influence clean energy investments. This aligns with the findings of Orola et al. (2024), which show that mineral price volatility can significantly and negatively impact the social life cycle assessments of battery materials, ultimately making clean energy technologies less cost-competitive than conventional fossil fuels. Likewise, Fazlollahi & Ebrahimijam (2017) observed that clean energy sectors are driven by oil price volatility in the long-term. Regarding volatility connectedness, Asl et al. (2021) found that shocks in the OVX index significantly impact on clean energy stocks. Similarly, Shahid et al. (2023) reported a negative correlation between the volatility indexes of commodities and clean energy investments.

In broader context, Zhang et al. (2025) investigate the structural impacts of new energy mineral prices on green securities markets, utilizing advanced econometric models such as the TVP-SVAR-SV and MSVAR. Their study effectively captures the dynamic and regime-dependent nature of price volatility, offering a more understanding of short-to medium-term fluctuations. Similarly, Attílio (2025b) examines the role of critical mineral prices in shaping the global energy transition, incorporating an empirical model that considers the international spillover effects of mineral price shifts, and found economic interdependencies and the cross-border transmission of energy transition costs. Focusing on transmission mechanisms, Islam and Sohag (2024) analyze global transmission mechanisms and volatility spillover effects of mineral and oil prices in renewable energy production, employing partial cross-quantilogram (PCQ) and rolling window-based recursive cross-quantilogram (RCQ) methods. Their findings show that mineral price shocks bolster renewable energy generation in bullish market conditions. Contrary to the discussion above, Dutta et al. (2023) argued that rising climate risk can drive increased investment in clean energy, which in turn creates a ripple effect by reducing inherent volatility levels.

Therefore, this study evaluates the following null hypothesis:

Hypothesis 1. Mineral volatility has no significant impact on the clean energy transition.

2.3. ESG uncertainty and clean energy sector

As the globe moves toward sustainable development, the combination of Environmental, Social, and Governance (ESG) elements in the clean energy sector is becoming ever more important. Different uncertainties affect this change, including environmental, political, and financial ones that affect ESG performance and investment choices in the clean energy sector. Studies have revealed that while they demonstrate resilience in some situations, clean energy investments are susceptible to climate policy uncertainty (CPU). For instance, Abakah et al. (2024) state that uncertainty in monetary policy has a detrimental impact on ESG performance in the clean energy industry. This implies that maintaining investments in clean energy depends on stable and open financial regulations. Using a Generalized Method of Moments (GMM) model on a sample of 1738 firms across 22 European countries from 2017 to 2023, Ayadi et al. (2025) confirmed that Economic Policy Uncertainty (EPU) hurts ecological performance, ultimately leading to a decline in the clean energy sector. Supporting this view, Iqbal et al. (2023) find that economic policy uncertainty (EPU) influences the clean energy transition, ultimately driving progress toward clean energy adoption. In China, Iqbal et al. (2024) examined the asymmetric impacts of daily

Chinese climate policy uncertainty and found that it lowers carbon emission allowance prices while increasing the ESG index in the long run, ultimately supporting the growth of cleaner energy sources. This contrasts with the findings of Parashar et al. (2024), who demonstrated that ESG disclosure positively impacts the financial performance of renewable and clean energy companies. Sim and Zhou (2015) argued that ESG ratings foster low-carbon investments in clean energy firms by easing financing constraints and mitigating internal control risks, ultimately driving significant investments in clean energy sectors. Supporting this perspective, Li and Xu (2024) further confirmed that ESG ratings help alleviate financing constraints, enabling companies to invest more effectively in low-carbon projects (clean energy). Similar results were found by Tlaty et al. (2024), which underline the need of including ESG evaluations into investment strategies in clean energy in order to help lower risks.

Chen and Nouseen (2025) established that clean energy transitions is driven by the connection between energy security, and economic policy uncertainty. Bakhsh et al. (2024), using quantile analysis, demonstrate that environmental governance and economic complexity support the energy transition, while geopolitical interactions have varying effects across different quantiles. In the context of G7 nations, Yasmeen and Shah (2024), using MMQR regression, assess the impact of geopolitical conflict and energy uncertainty, arguing that both disrupt the energy supply chain and hinder the clean energy transition. This is further reinforced by Dai et al. (2025), who highlight that economic policy uncertainty negatively impacts overall energy consumption in G7 countries and adversely affects renewable energy utilization. Blyth and Sullivan (2017) emphasize that a lack of government commitment and unclear policy can deter investors from pursuing lasting projects, thereby hindering the adoption of clean energy. This finding is not unique, as Castrejon-Campos et al. (2020) also report the same outcome that energy-related policies play a crucial role in shaping the speed of clean energy transitions. A well-structured regulatory framework strengthens economic policy certainly by ensuring clear, consistent, and enforceable policies. In the BRICS countries, Zhang and Razzaq (2022), using parametric estimators, found that economic policy certainly slows the clean energy transition. Similarly, Zhang et al. (2021) and Zeng and Yue (2022) reported that economic policy uncertainty (EPU) negatively impacts clean energy consumption.

In contrast, other studies differ from the foregoing showcasing that reducing the cost uncertainty can impact on clean energy sector. For instance, Tang et al. (2019) establish in China that decreasing costs of renewable energy play a crucial role in advancing power generation technologies and enhancing clean power transmission, while increasing the share of renewable energy in China's power sector. Romano and Fumagalli (2018) posit that electricity cost creates substantial uncertainty, influencing the adoption and implementation of low-carbon technologies (clean energy). The conclusion of Chapman et al. (2021) offers a slightly different global perspective, finding that social acceptance of emerging technologies and fairness in equity are strongly correlated with the deployment of new renewable energy sources. In Sydney, Cheung et al. (2019) identify social and environmental responsibility uncertainties as key factors influencing regional renewable energy adoption. Finally, Wei et al. (2024) explores the potential role of climate policy uncertainty (CPU) using DCC-MIDAS model document that a long-run negative correlation between clean energy and different energy metal indicating potential implications for investment performance in the clean energy sector.

Therefore, this study evaluates the following null hypothesis:

Hypothesis 2. ESG uncertainty has no significant impact on the clean energy transition

2.4. Research gap

Though a lot of research has been done on the resource curse theory and financial risk theories in connection to mineral price volatility, ESG uncertainty, and the clean energy transition, significant gaps yet go unpacked. Especially in terms of investment risks, supply chain disruptions, and the economic viability of renewable technologies, the current research have shed important light on how mineral price volatility influences the clean energy sector. Still under exploration, though, is the interaction between ESG-driven financial instability and the renewable energy transition. Although few research have evaluated how ESG criteria shape investor behavior, nothing has been studied on how ESG-related uncertainties affect mineral price volatility and, hence, the course of adoption of clean energy.

First of all, the empirical studies on the clean energy sector and mineral volatility mostly concentrate on macroeconomic elements influencing mineral markets and geopolitical concerns. Still lacking enough research is the impact of ESG-driven investment behavior, legislative changes, and sustainability issues on price volatility. Although several research have found that geopolitical tensions affect commodity markets, there is a dearth of studies including ESG issues into the larger framework of mineral price dynamics and their consequences for clean energy supply chains.

Second, although ARCH/GARCH models have been used to explain volatility clustering in energy markets, their use in comprehending the impact of ESG-related uncertainty on mineral price swings is still restricted. Further research is needed to determine how investor attitude, ESG disclosure rules, and negative ESG events could all help to increase market volatility. Though the possible magnifying effects of ESG uncertainty on mineral markets and clean energy investments remain an issue needing more research, existing studies have investigated financial volatility related with economic policy uncertainty and geopolitical threats.

Third, the body of research evaluating how ESG uncertainty affects the shift to clean energy is disjointed. Although some research show how financial regulation instability and economic policy uncertainties affect clean energy investments, others contend that ESG factors encourage long-term renewable energy investment. But knowledge of the feedback loop between the financial sustainability of the renewable energy sector and ESG-induced resource price volatility lags far behind. Still mostly unknown is how much ESG regulation changes shape investor confidence, influence renewable energy prices, and change long-term energy transition paths.

Fourth, studies evaluating renewable energy transitions in relation to ESG uncertainty sometimes center on industrialized or high-income countries. Research examining how ESG-driven volatility influences developing nations and their capacity for a switch to renewable energy is lacking. Mineral-rich developing nations are major providers of important raw materials as lithium and cobalt, hence the effects of ESG uncertainty on their economy, energy security, and transition plans are neglected.

Ultimately, the interdependence between these elements and ESG uncertainty remains poorly known even while empirical research have examined economic policy uncertainty (EPU), climate policy uncertainty (CPU), and geopolitical concerns in respect to energy markets. By use of sophisticated econometric models like structural equation modeling (SEM) and volatility spillover frameworks, one can get fresh understanding of the cross-sectoral effects of ESG uncertainty, mineral price volatility, and the clean energy transition.

3. Data and methodology

3.1. Data

This study aims to investigate the relationship between ESG uncertainty (ESGU) and volatility of critical minerals for clean energy transition. To achieve this objective, we utilize the monthly data spanning from November 2002 to September 2024, determined by the available ESGU data. In this study, among critical minerals, we use copper, zinc,

platinum, lead, silver, and nickel.[1] Furthermore, we measure the volatility of critical minerals via the MF2-GARCH volatility estimated by The Volatility Laboratory of the NYU Stern Volatility and Risk Institute.[2]

3.2. Justification for the selection of critical minerals and volatility measures

The selection of copper, zinc, platinum, lead, silver, and nickel is justified by their vital roles in clean energy technologies, high-tech industries, and national security (Cook, 2024). Copper is essential for electrical systems and renewable energy infrastructure; zinc for steel galvanization and batteries; nickel for stainless steel and battery storage (Cook, 2024). Platinum is crucial for catalytic converters and fuel cells (Blaschke et al., 2015); lead remains important for batteries and radiation shielding; and silver is key for electronics and solar panels (Bieñko et al., 2023). Beyond their technological relevance, these minerals face heightened supply chain risks driven by geopolitical constraints, resource concentration, and surging global demand, further reinforcing their critical status.

To robustly capture the dynamic and complex nature of price fluctuations in these mineral markets, we measure volatility is measured using the MF2-GARCH model, as estimated by The Volatility Laboratory at NYU Stern. This advanced method captures the multifractal and dynamic nature of commodity price fluctuations more accurately than simpler models, providing a robust basis for analyzing risk transmission in critical mineral markets (Seiler, 2024). The details for the utilized data series are provided in Table 1.

The utilized monthly dataset for this study is presented in Fig. 1. Here, it is important to note that critical minerals volatility was obtained on a daily frequency due to data availability. Monthly critical minerals volatility was calculated by averaging the available daily volatility values in each month.

3.3. Empirical model

The study relied on the quantile-on-quantile regression (QQR) technique of (Sim and Zhou, 2015) to explore the quantile marginal effects of ESG uncertainties on critical minerals volatility. This novel technique is selected to provide, with precision, the quantile dependence structure of the verified relationship. The choice of the QQR procedure is predicated on its verified attributes. Notably, the QQR technique is a bivariate econometric technique that captures the intricate dynamics between two variables over their respective quantile distributions (Gohar et al., 2023; Sim and Zhou, 2015; Sulong et al., 2024). Unlike the traditional regression techniques, the QQR procedure combines the attributes of both the traditional and the quantile nonparametric procedures for a granular account of the quantile dependencies of both the predicting and predicted variables. Following the specification of (Sim and Zhou, 2015), the quantile-on-quantile dynamic relationships of ESG uncertainty and the critical minerals volatility are captured in Eq. 1

$$CMV_t = \beta^{\lambda}(ESGU_t) + \sum_{i=1}^{n} \alpha^{\lambda}(X_t) + \sum_{i=1}^{n} \gamma^{\lambda}(ESGU^{*}X_t) + \varepsilon^{\lambda} \tag{1}$$

In Eq. (1), CMV_t depicts critical mineral volatility, $ESGU_t$ represents ESG uncertainty, X_t refers to uncertainty factors, ε is the stochastic error term in each λ quantile. When interactions are allowed within the relationship in Eq. (1), the resulting specification is captured thus:

$$CMV_t = \phi^{\lambda}(ESGU_t) + \sum_{i=1}^{n} \alpha^{\lambda}(X_t) + \varepsilon^{\lambda} \tag{2}$$

In Eq. (2), the unknown function is depicted by ϕ^{λ} given that the moderating effects of the exogenous series on critical mineral volatility are unknown. To assess the unknown function, an expanded first-order Taylor function ϕ^{λ} is approximated in Eq. (3).

$$\phi^{\lambda}(ESGU_t) \approx \phi^{\lambda}(ESGU^{\tau}) + \phi^{\lambda^{i}}(ESGU^{\tau})(ESGU_t - ESGU^{\tau}) \tag{3}$$

Where in Eq. (3), $\phi^{\lambda}(ESGU^{\tau})$ and $\phi^{\lambda^{i}}(ESGU^{\tau})$ are indexed in λ and τ, while $ESGU^{\tau}$ is captured only in τ. When the specified values of Eq. (2) are replaced, the resulting mechanism is expressed in Eq. (4).

$$\underbrace{CMV = \phi_0(\lambda,\tau) + \phi_1(\lambda,\tau)(ESGU_t - ESGU^{\tau}) + \sum_{i=1}^{n} \alpha^{\lambda}(X_t) + \varepsilon^{\lambda}}_{(*)} \tag{4}$$

In Eq. (4), the numerator (*) represents the λ^{th} quantile of critical mineral volatility, contingent on the τ^{th} of ESG uncertainty. The (*) also gauges the implications of the exogenous variable. On account of this ratification, Eq. (4) is expanded thus:

$$\begin{aligned} CMV = {} & \phi_0(\lambda,\tau) + \phi_1(\lambda,\tau)(ESGU_t - ESGU^{\tau}) + \sum_{i=1}^{n} \{\alpha^{\lambda}(X_t) + \varepsilon^{\lambda} \\ & \underbrace{+\rho_1(\lambda,\tau)(X_t ESGU_t - X^{\tau} ESGU^{\tau})\} \sum_{i=1}^{n} a(\lambda)(X_t)}_{(*)} \end{aligned} \tag{5}$$

Accordingly, the (*) part in Eq. (5) depicts the total dependence structure of critical mineral volatility on ESG uncertainty amidst the influence of the exogenous variable. Eq. (5) is expanded into Eq. (6) to account for optimization.

$$\min_{\phi_0,\phi_1,\rho_0,\rho_1} \sum_{i=1}^{n} \varphi_{\lambda} \left[CMV_t - \phi_0 - \phi_1(ESGU_t - ESGU^{\tau}) - \sum_{i=1}^{n} \{\rho_0 + \rho_1(X_t ESGU_t - X^{\tau} ESGU^{\tau})\} + \sum_{i=1}^{n} a(\lambda)(X_t) \right] K\left(\frac{F_q(ESGU_t) - \lambda}{h}\right) \tag{6}$$

In Eq. (6), the estimated values are expressed as $ESGU_t - ESGU^{\tau}$ and $X_t ESGU_t - X^{\tau} ESGU^{\tau}$. Meanwhile, the retained minimal bandwidth is expressed in Eq. (7).

$$F_q(ESGU_t) = \frac{1}{q} \sum_{q-1}^{n} 1(ESGU_b < ESGU_t) \tag{7}$$

In Eq. (7), the estimated bias is retained at a minimal bandwidth $h = 0.05$.

[1] These critical minerals are those for which volatility series are available at https://vlab.stern.nyu.edu from the minerals given in https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer.

[2] Although The Volatility Laboratory of the NYU Stern Volatility and Risk Institute provides volatility series calculated using different volatility methods, the MF-GARCH volatility method is preferred in this study as it is more recent than other volatility methods. Additionally, we also utilize different volatility measurement of critical minerals for the robustness check.

Table 1
Data description.

Variable	Symbol	Proxy	Source
ESG Uncertainty	ESGU	Global GDP weighted ESG-Related Uncertainty Index created by Ongan et al. (2025)	https://www.policyuncertainty.com/
Copper Volatility	COPV	S&P GSCI Copper Spot Index MF2-GARCH Volatility	https://vlab.stern.nyu.edu
Zinc Volatility	ZINCV	S&P GSCI Zinc Index MF2-GARCH Volatility	https://vlab.stern.nyu.edu
Platinum Volatility	PLATV	S&P GSCI Platinum Index MF2-GARCH Volatility	https://vlab.stern.nyu.edu
Lead Volatility	LEADV	S&P GSCI Lead Spot Index MF2-GARCH Volatility	https://vlab.stern.nyu.edu
Silver Volatility	SILV	S&P GSCI Silver Index MF2-GARCH Volatility	https://vlab.stern.nyu.edu
Nickel Volatility	NICV	S&P GSCI Nickel Spot Index MF2-GARCH Volatility	https://vlab.stern.nyu.edu

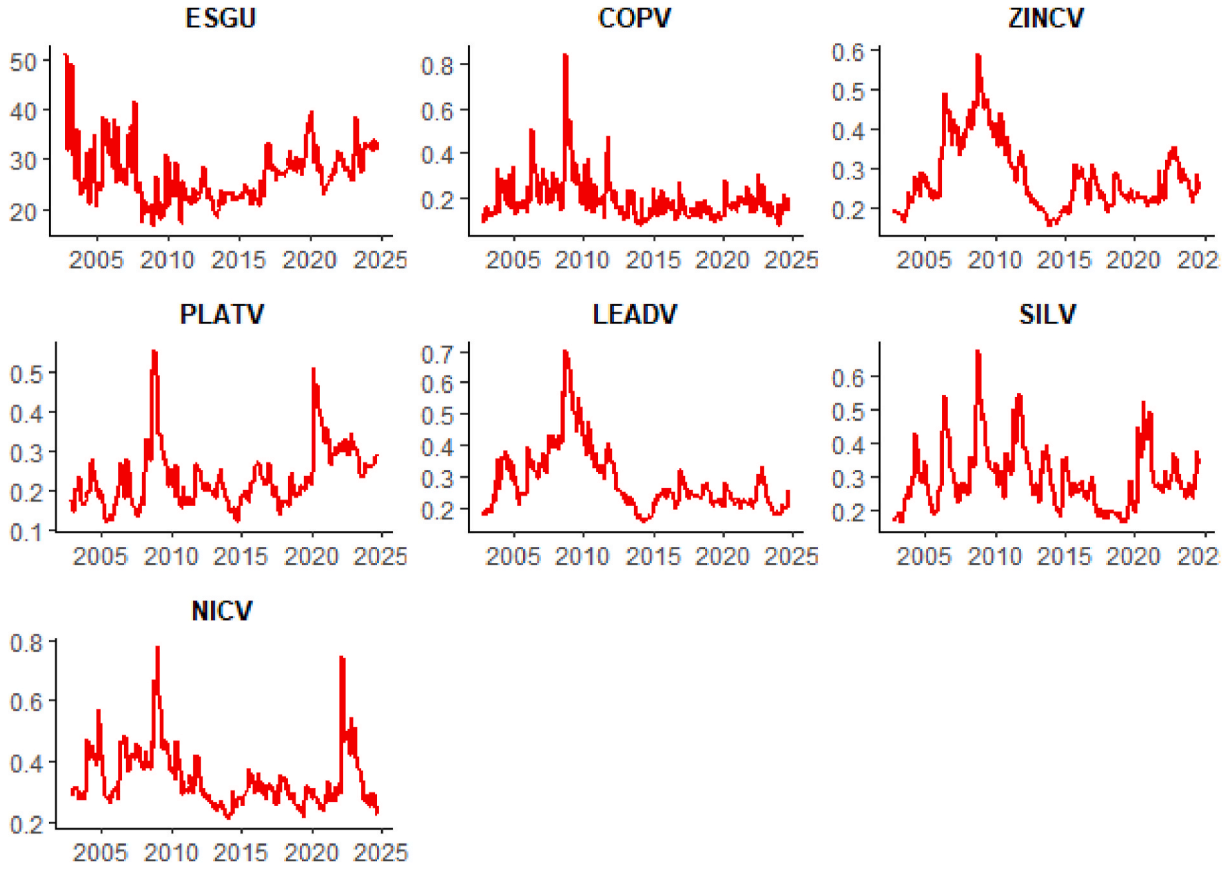


Fig. 1. Monthly ESGU index and critical minerals volatility from November 2002 to September 2024.

Table 2
Descriptive statistics.

	ESGU	COPV	ZINCV	PLATV	LEADV	SILV	NICV
Mean	26.993	0.191	0.281	0.233	0.286	0.301	0.342
Median	26.224	0.169	0.256	0.216	0.250	0.283	0.310
Max	51.042	0.841	0.589	0.555	0.701	0.672	0.775
Min	16.570	0.070	0.153	0.118	0.152	0.166	0.212
SD	5.537	0.091	0.088	0.076	0.101	0.094	0.093
Skewness	0.904	2.523	1.015	1.425	1.551	1.138	1.568
Kurtosis	4.404	13.856	3.428	5.753	5.664	4.594	6.290
Jarque-Bera	57.460*	1570.431*	47.191*	172.100*	183.212*	84.602*	226.308*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ARCH-LM(1)	7.565*	6.110*	33.162*	23.276*	36.316*	23.013*	11.076*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note: * denotes (Pr) $\leq$ 0.01.

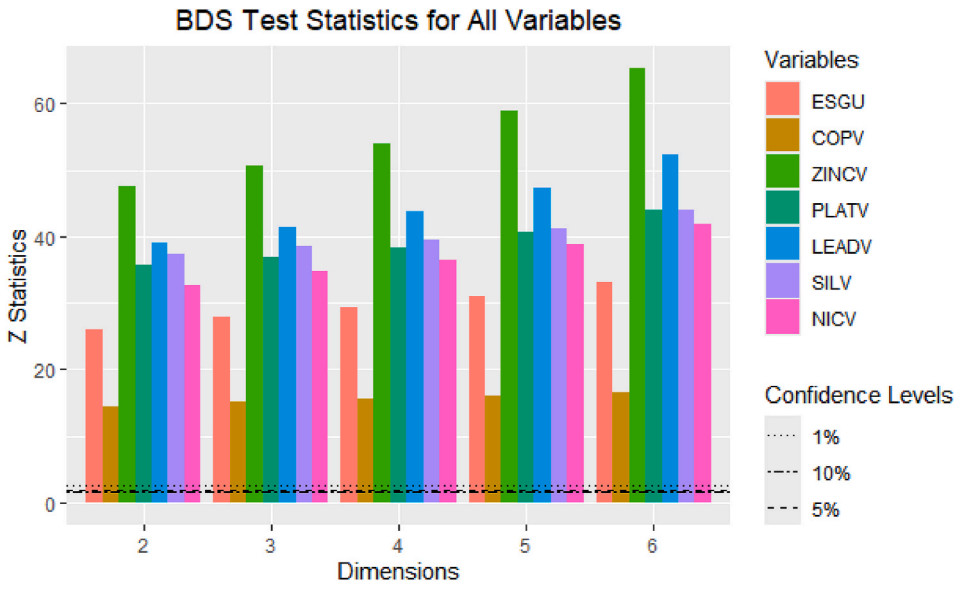


Fig. 2. BDS test.

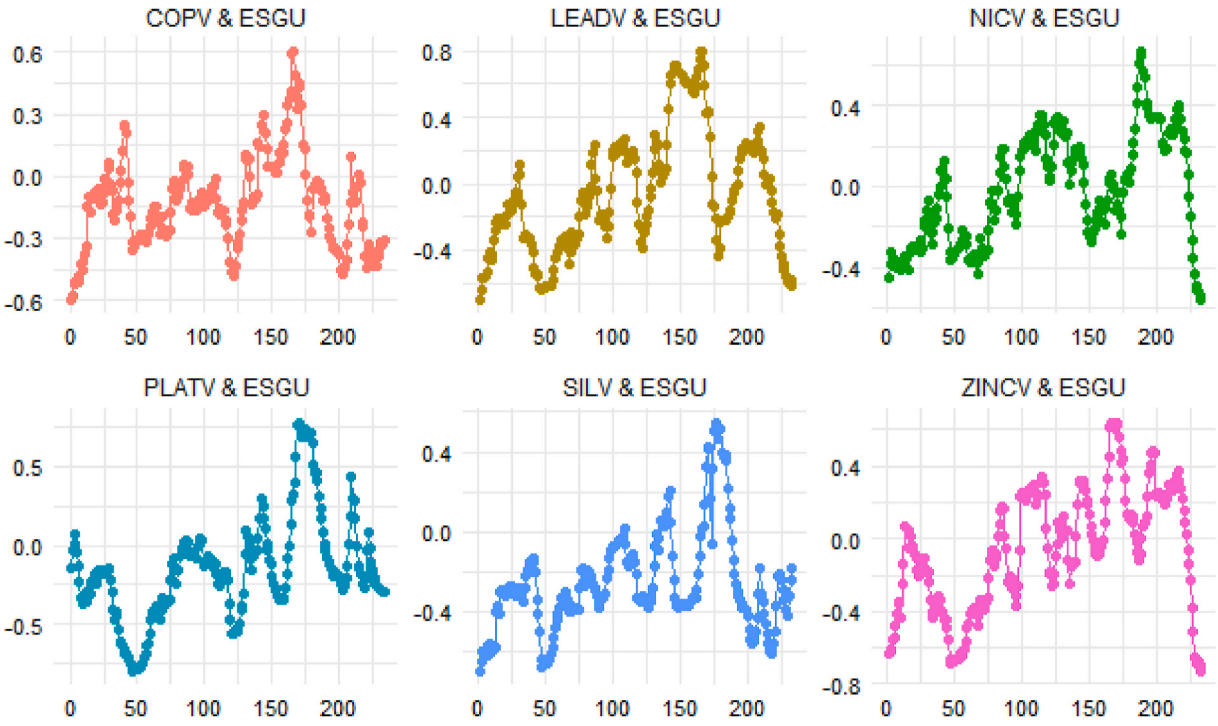


Fig. 3. Rolling window correlations between ESGU and critical minerals volatility.

4. Results and discussions

4.1. Results

The outcomes of the descriptive statistics (Table 2) and the nonlinearity test via the BDS test (Broock et al., 1996) procedure (Fig. 2) provide relevant insights into the nature of the selected variables. Essentially, the summarized outcomes underscore the distributional properties and nonlinear nature of the variables, amplifying the need for the application of robust nonlinear and time-sensitive quantile-based estimators. Hence, the application of the rolling window correlation, quantile PSS bounds test, quantile causality, and quantile-on-quantile regression are prominently justifiable.

The rolling window correlation plots (Fig. 3) extend further insight into the nature of the association between ESG and critical minerals volatility. The rolling window correlation uncovers the time-changing association between ESG and the selected critical minerals. Notably, the observed associations are changing in magnitude, scale, and direction, highlighting the possibility of quantile dependence interactions among the series. Further insights into the long-term coevolution of the series are illustrated with the quantile Pesaran, Shin, and Smith (QPSS) bounds (Adebayo et al., 2025) bounds test (Fig. 4). Instructively, the figure demonstrates notable quantile-based long-term convergence between ESG-uncertainty and the critical minerals volatility. These outcomes provide further justification for the applications of the selected time-sensitive quantile-based estimators.

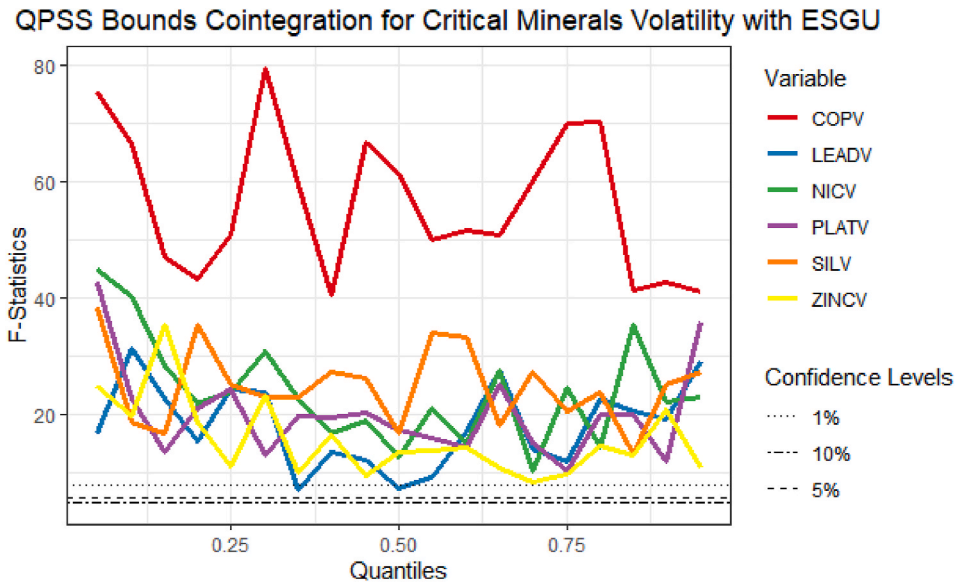


Fig. 4. QPSS bounds test.

The causal effects dynamics of ESG and the critical minerals volatility are illustrated with the quantile causality (QC) (Troster, 2018) plots depicted in Figure (5). As earlier stated, unlike the traditional Granger causality protocols that report only the conditional causal effects, the QC instead reports the causal effects across the quantile distributions of the series. Through this technique, the granular quantile causal effects of ESG uncertainty and critical minerals volatility are ascertained. Accordingly, the evidence portrayed in Fig. 5 demonstrates the quantile-sensitive Granger causal effects of ESG uncertainty and critical minerals volatility. It is particularly notable that the causal effects of ESG uncertainty on each critical mineral volatility occurred at the lower quantiles and spread across this entire distribution. The exception to this inference is Copper (Fig. 5a) and Silver (Fig. 5d) volatilities, where significant causal effects were not recorded beyond the middle quantile. Overall, this established evidence portrays ESG uncertainty as a crucial driver of critical minerals volatility. Hence, the understanding of the marginal effects of ESG uncertainty on the quantile distributions of critical mineral volatility possesses strong policy appeal for sustained global clean energy transition.

As earlier highlighted, this study applied the novel quantile-on-quantile regression (QQR) econometric toolkit credited to (Sim and Zhou, 2015). Herein, Fig. 6 depicts the outcomes of the marginal effects of ESG uncertainty on critical minerals volatility. Remarkably, these outcomes are ratified across the quantile distributions of both variables (predicting and predicting). The QQR legends range from positive (thick red background) to negative (thick blue) interactions. Accordingly, the plots underscore the obvious heterogeneous association between ESG uncertainty (ESGU) and each of the incorporated critical minerals volatility. For copper volatility (COPV), the evidence (Fig. 6 a) portrays a substantial negative association with ESGU at its upper quantiles and at the lower quantiles of ESGU. Moving along the distributions, there are traces of neutral and moderate marginal effects, particularly at the middle quantiles of ESGU and COPV. Meanwhile, there is a trace of substantial positive affiliation between ESGU and COPV in the uppermost-quantile of ESGU and COPV. This buttresses the essence of the application of this unique time-specific sensitive estimator, given its ability to unearth context-specific attributes of economic relationships.

The quantile-on-quantile relationship between ESGU and zinc volatility (ZINCV) is depicted in Fig. 6b. Similar to COPV, a heterogeneous relationship exists between ESGU and ZINCV across their quantile distributions. Particularly, a substantial negative association exists between them across their lower quantiles towards the middle quantile of ESGU. Yet, traces of tenuous positive and negative affiliations are observable within the middle quantiles of both variables. At the upper quantiles (q0.95) of both variables, a substantial positive affiliation is established between ESGU and ZINCV. Furthermore, the prevailing relationship between platinum volatility (PLATV) and ESGU is illustrated in Fig. 6c. Accordingly, Fig. 6c portrays a substantial negative affiliation between ESGU and PLATV at the lower quantile (q0.25) of ESGU and at the upper quantiles (q0.75-q0.95) of PLATV. However, substantial positive affiliations are observed across the middle and upper quantiles of both variables. Besides, there are traces of tenuous positive associations between the two variables at the upper quantile (q0.95) of ESGU and at the lower quantile (q0.25-q0.5) of PLATV. Notably, this highlighted evidence portrays significant heterogeneous marginal effects of ESGU and each critical mineral volatility, underscoring the need for context-specific policy adjustments for the realization of clean energy transition.

The quantile relationship between ESGU and Lead volatility (LEADV) is represented by Fig. 6d. Similar to its marginal effects on COPV and ZINCV, ESGU possesses heterogeneous quantile-sensitive affiliations with LEADV, which range from the lower to the upper quantiles. Specifically, negative associations exist between ESGU and LEADV at the lower quantiles (q0.05-q0.25) of ESGU and across the lower (q0.25), middle (q0.50), and upper quantiles (q0.75-q0.95) of LEADV. At the middle quantiles (q0.50-q0.75) of ESGU and within the middle (q0.50-q0.75) to upper quantiles (q0.95) of LEADV, varying minimal positive and negative affiliations are established between the two variables. Notably, there is evidence of substantial positive associations between ESGU and LEADV at the upper quantiles of the distributions of both variables.

Similar attributes prevail between ESGU and Silver volatility (SILV), as well as ESGU and nickel volatility (NICV). Accordingly, substantial negative affiliations are established at the lower quantiles (q0.05-q0.25) of ESGU and from the middle to upper quantiles of both SILV and NIVC. At the middle quantiles (q0.50-q0.75) of ESGU and SILV, diverging neutral positive and negative associations prevail between the two variables. Exert same attributes are established between ESGU and NICV at their respective middle quantiles. Although there is a trace of substantial positive affiliation between SILV and ESGU at the q0.75 and q0.95 quantiles of their respective distributions. Additionally, there is evidence of substantial positive affiliations between ESGU and SILV, as well as ESGU and NICV at their upper quantiles (q0.95). The observed varying associations between ESGU and these two notable critical

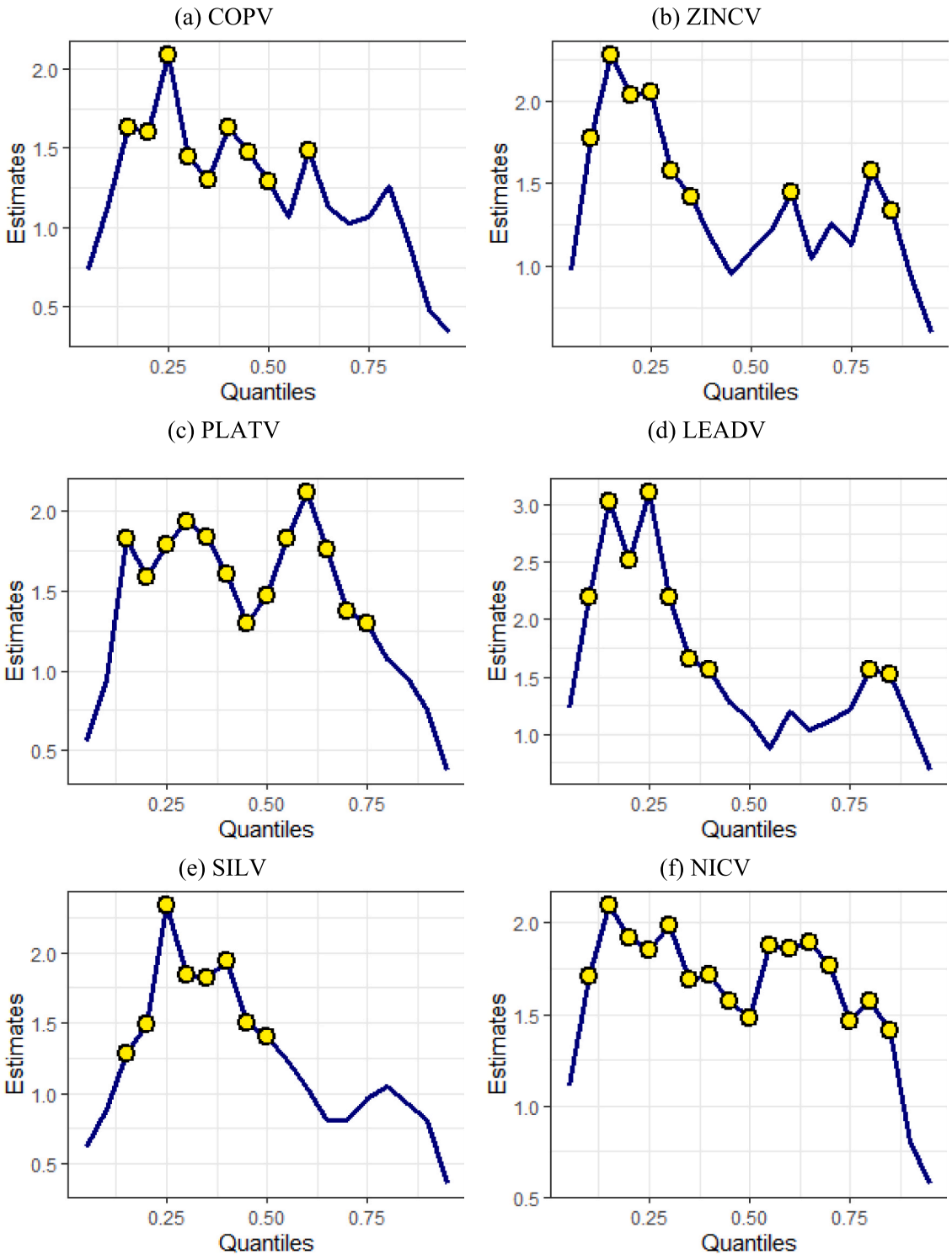


Fig. 5. QC results. Note: ⬡ denotes (Pr) ≤ 0.1.

minerals lend credence to the prominent heterogeneous and asymmetric association between them and ESGU.

4.2. Robustness evaluation

For robustness analysis, the analysis of the study is repeated using different volatility series for critical minerals. Herein, the repeated analysis is based on the GAS-GARCH Student T Volatility calculated by The Volatility Laboratory of the NYU Stern Volatility and Risk Institute. The data description, time trend plots, descriptive statistics, BDS test, and rolling window correlation estimates for the GAS-GARCH Student T Volatility are provided in the Appendix. Accordingly, the QPSS test, the quantile causality, and the QQR analysis of the GAS-GARCH Student T Volatility generated data are depicted in Figs. 7–9, respectively.

Similar to the original series, the long-term coevolution of the series generated through the GAS-GARCH Student T Volatility conforms to the expected outcomes. Accordingly, all the critical minerals are cointegrated in the long run. Hence, the null hypothesis, which suggests no

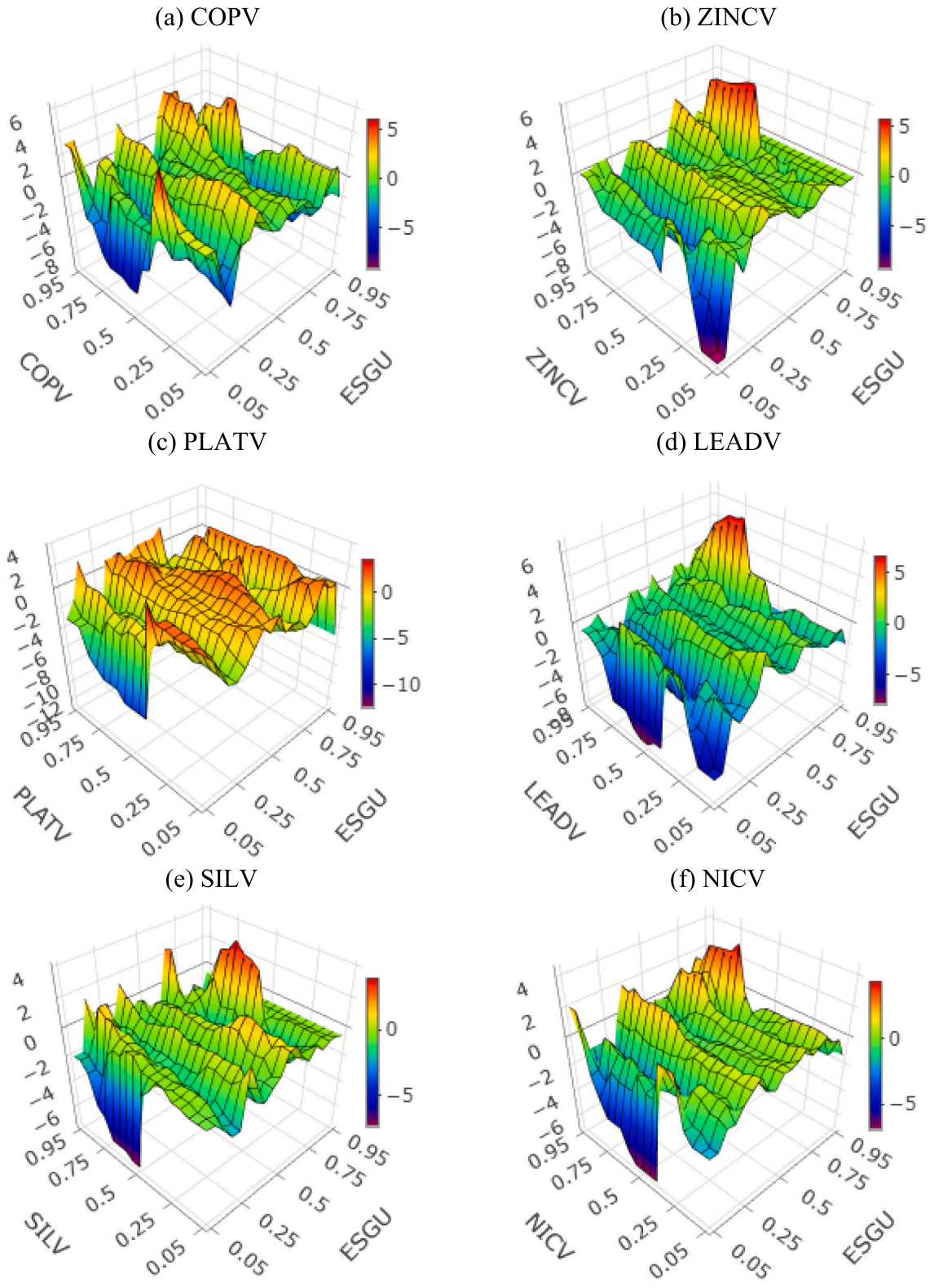


Fig. 6. QQR results.

long-term coevolution, is rejected. The quantile causality plots (Fig. 8) illustrate significant causal effects between ESGU and all the critical minerals at different quantiles. Notably, except for SILV (Fig. 8e), the significant causal effects stretch from q0.25 to q0.75. Based on these discoveries, it is evident that ESGU is a fundamental determinant of critical mineral volatilities. Hence, policies aimed at clean energy transition through the critical minerals must take cognizance of ESG uncertainties.

Further insights into the marginal effects of ESGU on the critical minerals volatility are drawn from the QQR plots depicted in Fig. 9. Evidently, the outcomes of the QQR robustness plots are prominently consistent with the baseline QQR analysis. Based on this evidence,

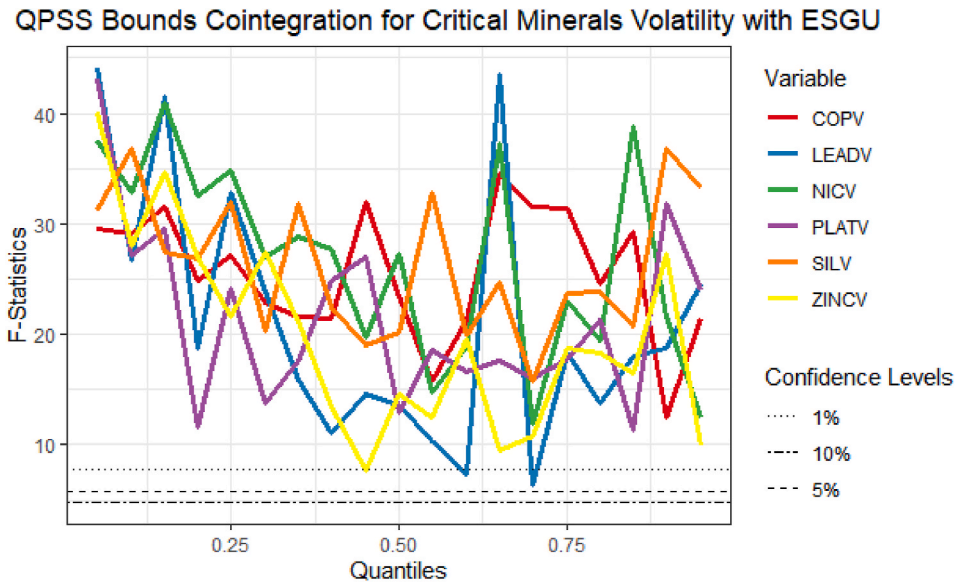


Fig. 7. QPSS bounds test.

countries desirous of a sustained clean transition should align their policies with the policy inferences of this study, given its in-depth analysis via cutting-edge estimators. Moreover, the consistency of the baseline and robustness tests of the applicable techniques is further testimony of the reliability of the discoveries and inferences of this study. Overall, this notable evidence eloquently highlights that the effects of ESG uncertainty must be considered in policies targeted at clean energy transitions through critical minerals.

4.3. Discussions of findings

This study verified the implications of ESG uncertainty on critical minerals volatility, given their critical roles in the global clean energy transition. The empirical analyses uncovered compelling insights critical for policy formulation and implementation toward clean energy transition. Particularly, the empirical evaluation underscores prominent heterogeneous and asymmetric effects of ESG uncertainty on critical minerals volatility.

This outcome possesses several implications for critical mineral markets and the transition to clean energy. Some prior studies (Abakah et al., 2024; Ayadi et al., 2025; Chen et al., 2024; Goutte and Mhadhbi, 2024) have highlighted the implications of heterogeneous and asymmetric associations among economic variables. Particularly, this outcome highlights the need for context-specific policy articulation that could minimize the adverse effects of ESG uncertainty on each critical mineral's volatility. Notably, these critical minerals are fundamental for clean energy transition; hence, reducing the adverse effects of ESG uncertainty on them will foster an accelerated transition to clean energies globally. Undoubtedly, the transmission of ESG uncertainties to critical minerals volatility is potentially a strong vulnerability to energy transition.

Expectedly, consistency in economic, social, and governance policy moderation is vital to curtailing the volatility of critical minerals, with extended harmonious effects toward clean energy transition. Generally, ESGU produces significant adverse impacts on all critical minerals, particularly at their upper quantiles, with neutral effects at their middle quantiles. Such an outcome reflects the resource curse theory suggesting that wealth may diminish the incentive for leaders to establish strong bureaucratic institutions, leading to governance challenges and exacerbating price fluctuations through ESG-related concerns. Given the consistent shift to green energies, such diverging effects constitute significant negativities and asymmetric effects on energy security planning (Attílio, 2025a; Chen and Nouseen, 2025; Coskun et al., 2023). This may require immediate intervention by strengthening environmental, social, and governance practices aimed at improving green transitions. The negative implications are particularly notable in platinum volatility ranging from lower to upper quantiles. This phenomenon arises when uncertain market conditions, including changes in ESG regulations and supply chain vulnerabilities, result in sustained price fluctuations (Orpiszewski et al., 2024). This outcome holds profound policy implications, given the critical roles of platinum in hydrogen fuel cells, EV production, and battery storage technologies.

More insights into the relationship between ESGU and the quantile distributions of critical minerals volatility highlight potential positive affiliations at the upper quantiles of both variables. This particular discovery connotes vital policy implications for the drive toward green transition. This entails that the volatility of the critical minerals is largely sensitive to heightened uncertainties transmitted from ESG. These uncertainties may affect clean energy market expectations and regulatory frameworks (Giese et al., 2019). This also validates the fact that ESG uncertainty has introduced additional layers of risk and unpredictability into mineral markets, influencing production costs, investment flows, and long-term supply chain sustainability (Broadstock et al., 2021). Hence, energy policymakers may need to factor these challenges into their planning and energy forecasting to reduce the susceptibility of clean energy supplies to critical minerals volatility.

4.4. Practical implications

Taken together, the quantile-specific findings illuminate the complex but actionable interplay between ESG uncertainty and critical mineral market dynamics. Lower ESG uncertainty regimes tend to moderate mineral price volatility, offering investors opportunities to allocate capital with greater confidence in stable returns, particularly when targeting companies with strong ESG performance. Conversely, the pronounced volatility at higher mineral quantiles (excluding platinum) highlights the need for vigilant risk management, including robust hedging strategies to insulate portfolios during periods of market turbulence and in the face of uncertainties. For both investors and clean energy manufacturers, these insights underscore the value of dynamic, context-aware strategies. Investors are well-advised to diversify across asset classes — blending green bonds, equities, and critical minerals — to navigate volatility spillovers more effectively. Meanwhile, manufacturers can leverage these signals to reinforce supply chain resilience,

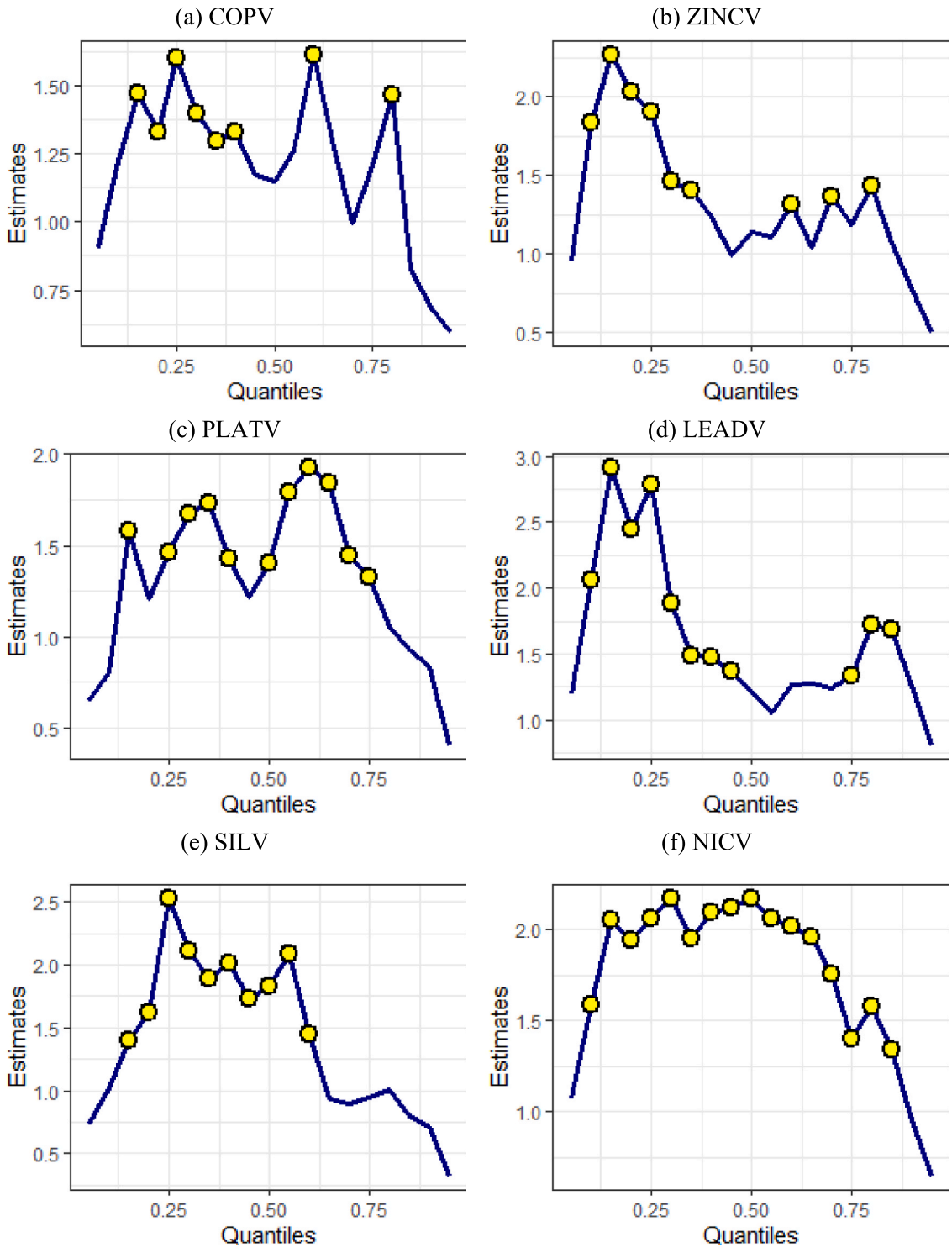


Fig. 8. QC results. Note: ⬤ denotes (Pr) ≤ 0.1.

secure long-term contracts, and diversify sourcing, thereby mitigating the cost and operational risks associated with critical mineral market shocks.

5. Conclusion and policy prescriptions

5.1. Conclusion

The potential susceptibility of a clean energy transition to volatility in critical minerals warrants the investigations of the potential drivers of such volatility. Whereas prior studies considered several factors, they, maybe inadvertently, failed to consider the potential implications of ESG uncertainty. This study filled this research gap by taking advantage of the recently launched ESG uncertainty to probe its contributions to critical minerals volatility. This study proceeded by implementing several novel estimators, including the rolling window correlation, quantile causality analysis, and the quantile-on-quantile regression on global data spanning from November 2002 to September 2024.

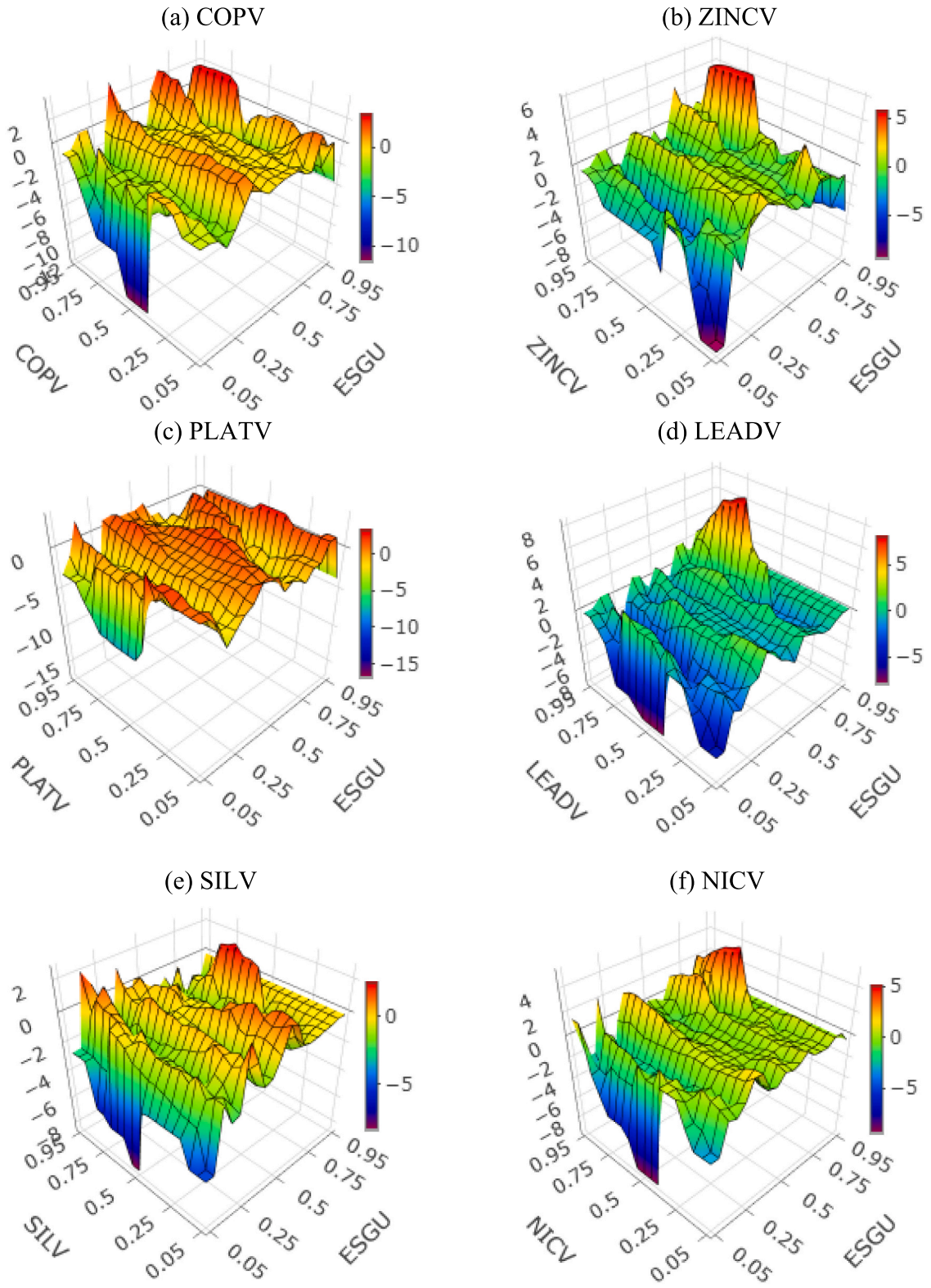


Fig. 9. QQR results.

Additionally, the study provided robustness evaluation by generating different volatility series for critical minerals based on the GAS-GARCH Student T Volatility calculated by The Volatility Laboratory of the NYU Stern Volatility and Risk Institute. Undoubtedly, the unique approaches and novel discoveries of this study unearth critical insights with profound policy implications for clean energy transitions.

5.2. *Policy prescriptions*

The findings of this study underscore the critical role of Environmental, Social, and Governance (ESG) uncertainty in shaping the volatility of critical minerals, which are essential for the clean energy transition. Given the heterogeneous and asymmetric nature of the

relationship between ESG uncertainty and mineral volatility, tailored policy responses are imperative to mitigate risks, ensure market stability, and foster a smooth transition to clean energy. Governments and regulatory bodies must establish stable and predictable ESG policies to minimize uncertainty in mineral markets. Clear and well-defined ESG regulations can reduce investor uncertainty and mitigate market fluctuations, thereby ensuring a steady supply of critical minerals. Policies should focus on enhancing transparency, enforcing environmental protection measures, and promoting responsible mining practices to align with clean energy goals. Additionally, financial institutions and policymakers should develop market-based risk management tools, such as ESG-indexed derivatives and hedging instruments, to help investors and stakeholders mitigate volatility risks. Central banks and financial regulators should integrate ESG uncertainty indicators into their macroprudential risk assessments to anticipate and respond effectively to financial shocks arising from ESG concerns.

To minimize disruptions caused by ESG-related volatility, governments should diversify supply chains by promoting domestic mineral exploration and fostering international partnerships. Strategic stockpiling of critical minerals can also serve as a buffer against supply shocks, ensuring that clean energy industries have access to stable raw material supplies. Investment in ESG-compliant projects should be encouraged through green bonds, ESG-focused funds, and sustainability-linked financial instruments. Policymakers should create incentives for institutional investors to prioritize ESG-aligned mining and energy projects, ensuring that capital flows support the long-term stability of mineral markets and clean energy initiatives. Moreover, technological advancements in mineral extraction and recycling can reduce dependency on volatile mineral markets. Governments should support research and development initiatives aimed at improving resource efficiency, developing alternative materials, and enhancing the circular economy for critical minerals. Policies that promote mineral recycling can mitigate supply constraints and reduce environmental impacts associated with mining activities.

Given the global nature of mineral markets, international cooperation is crucial to managing ESG uncertainty and ensuring a stable transition to clean energy. Governments should engage in multilateral agreements and policy coordination efforts to harmonize ESG standards, reduce regulatory fragmentation, and facilitate cross-border investment in sustainable mining and clean energy technologies. Establishing comprehensive ESG monitoring systems to track ESG-related risks and their potential impact on mineral markets is essential. Early warning systems that incorporate real-time data analytics can help stakeholders anticipate and mitigate ESG-driven volatility, ensuring proactive policy responses to market disruptions. Policymakers must also ensure that clean energy transition strategies are aligned with ESG goals by integrating sustainability criteria into energy policies. Incentives for clean energy technologies should include ESG considerations, ensuring that the transition to renewables does not exacerbate social or environmental risks associated with mineral extraction and processing. Policymakers should refine and harmonize ESG-related regulations to better enable clean energy manufacturers to meet their sustainability objectives. This entails establishing clear, actionable community engagement frameworks and promoting a balanced regulatory environment that aligns business viability with robust environmental stewardship. By implementing these policy prescriptions, stakeholders can address the volatility of critical minerals, mitigate ESG-induced risks, and facilitate a more stable and sustainable clean energy transition.

5.3. Limitations and suggestions for further studies

In tandem with its stated objectives, we presented only a global perspective of ESG uncertainty - critical minerals volatility association. This option might limit the implementation of the policy options provided herein, given the peculiarities of individual economies. Hence, country-specific inquiries are critical for understanding the peculiarities of each country vis-à-vis ESG uncertainty - critical minerals volatility association. Besides, countries differ in both commitment and consistency in clean energy transition policies. Thus, country-specific studies that ratify the depth and differences in each country could ensure a plausible transition for each economy. Not least, future studies could harness other novel econometrics tools to verify the implications of ESGU on critical minerals volatility. A global perspective or country-specific dimensions are respectively noteworthy.

CRediT authorship contribution statement

Oktay Ozkan: Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emmanuel Uche:** Writing – review & editing, Writing – original draft, Resources, Data curation, Conceptualization. **Chinazaekpere Nwani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources. **Kingsley I. Okere:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, we used Grammarly in order to improve the language and readability of this manuscript. After which, we reviewed and edited the contents as needed and take full responsibility for all the content of the publication.

Declaration of competing interest

All the authors agreed to the submission of this manuscript to this journal. Likewise, the study did receive any special funding, hence there is no conflict of interests of any kind.

Appendix

Table A1
Robustness data description

Variable	Symbol	Proxy	Source
Copper Volatility	COPV	S&P GSCI Copper Spot Index GAS-GARCH Student T Volatility	https://vlab.stern.nyu.edu
Zinc Volatility	ZINCV	S&P GSCI Zinc Index GAS-GARCH Student T Volatility	https://vlab.stern.nyu.edu
Platinum Volatility	PLATV	S&P GSCI Platinum Index GAS-GARCH Student T Volatility	https://vlab.stern.nyu.edu
Lead Volatility	LEADV	S&P GSCI Lead Spot Index GAS-GARCH Student T Volatility	https://vlab.stern.nyu.edu
Silver Volatility	SILV	S&P GSCI Silver Index GAS-GARCH Student T Volatility	https://vlab.stern.nyu.edu
Nickel Volatility	NICV	S&P GSCI Nickel Spot Index GAS-GARCH Student T Volatility	https://vlab.stern.nyu.edu

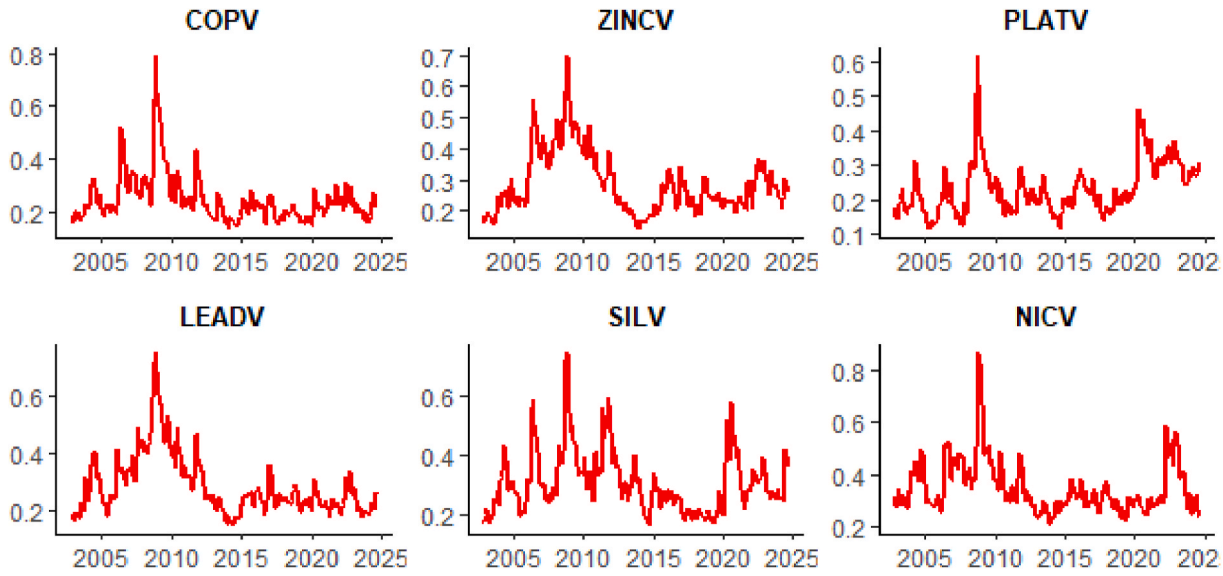


Fig. A1. Monthly critical minerals GAS-GARCH Student T volatility from November 2002 to September 2024

Table A2
Descriptive statistics for critical minerals GAS-GARCH Student T volatility

	COPV	ZINCV	PLATV	LEADV	SILV	NICV
Mean	0.244	0.288	0.236	0.289	0.311	0.347
Median	0.223	0.256	0.218	0.254	0.285	0.316
Max	0.788	0.695	0.614	0.744	0.746	0.868
Min	0.135	0.144	0.118	0.153	0.167	0.204
SD	0.091	0.097	0.079	0.105	0.104	0.099
Skewness	2.488	1.130	1.344	1.631	1.292	1.773
Kurtosis	11.533	4.033	5.723	6.047	5.018	7.952
Jarque-Bera	1069.185*	67.687*	160.482*	218.262*	117.826*	406.450*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ARCH-LM(1)	22.879*	23.858*	23.764*	38.112*	20.815*	17.225*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note: * denotes (Pr) $\leq$ 0.01.

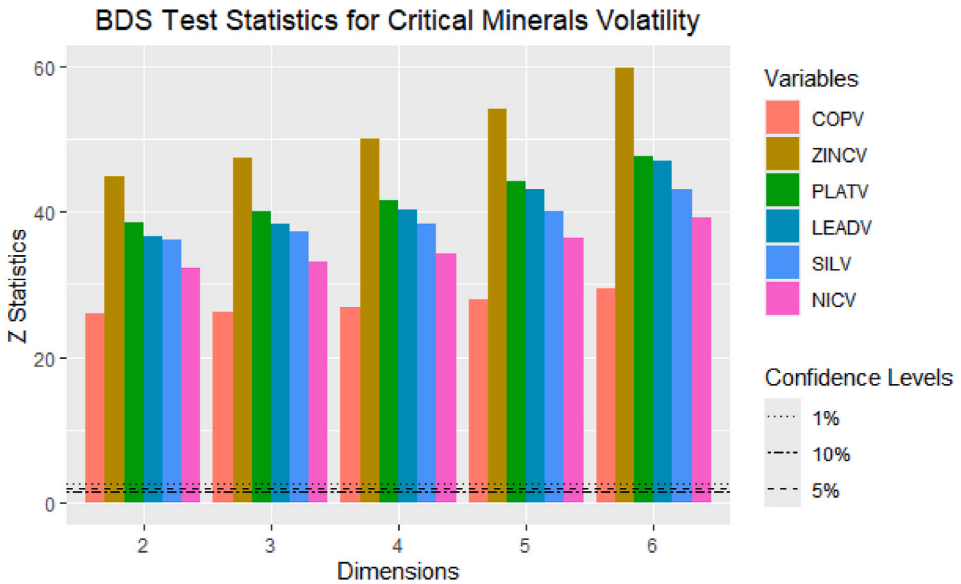


Fig. A2. BDS test for critical minerals GAS-GARCH Student T volatility

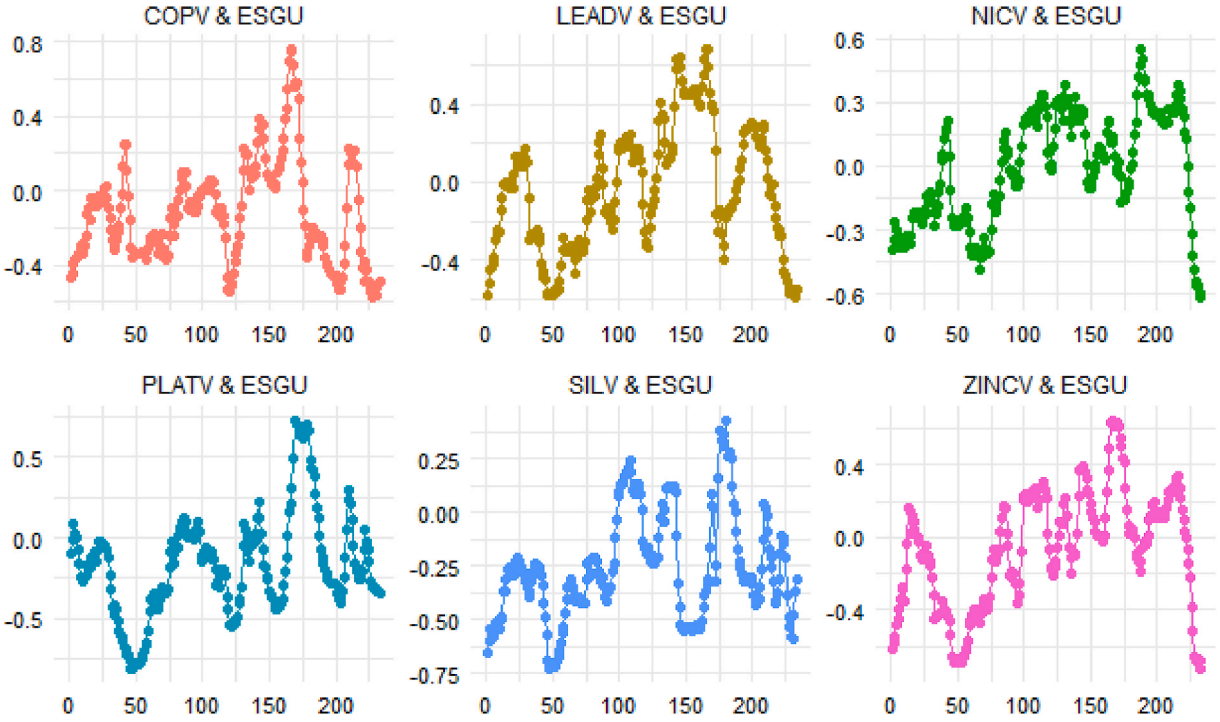


Fig. A3. Rolling window correlations between ESGU and critical minerals GAS-GARCH Student T volatility

Data availability

Data will be made available on request.

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