

Mineral Criticality Meets Energy Security: Quantifying the Import Dependency-Energy Transition Nexus in Advanced Clean Energy Economies

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Abstract. The global expansion of clean energy systems has significantly increased advanced economies' demand for critical minerals, raising concerns about trade dependency and supply security. This study examines how renewable energy installation capacity affects critical mineral import dependency in nine major renewable energy-producing advanced economies from 1990 to 2023, controlling for mineral and oil prices, exchange rates, economic growth, and geopolitical risks. To account for heterogeneous effects across market conditions, the analysis employs the Method of Moments Quantile Regression (MM-QR). The results reveal a consistently positive and significant relationship between renewable capacity and mineral imports across all quantiles, confirming the import-intensive nature of the clean energy transition. This effect is strongest in lower quantiles (slack markets) and moderates during import booms. Mineral prices exhibit regime-dependent effects, negatively impacting imports in slack markets but showing a positive relationship in booming conditions. Oil prices demonstrate a complementary effect, while exchange rates exert a negative influence, consistent with trade theory. Economic growth robustly stimulates import demand, whereas geopolitical risks persistently suppress mineral trade flows across all market states. The findings are robust to bootstrap quantile regression, Driscoll-Kraay standard errors, and high-dimensional fixed effects. Theoretically, the study extends trade theory by integrating geopolitical risk into an adapted Heckscher-Ohlin framework. A resilient policy framework must integrate counter-cyclical strategic stockpiling during slack markets, pursue diversified sourcing and allied "critical minerals club" cooperation to mitigate geopolitical risks, and accelerate innovation in material efficiency and recycling to fundamentally reduce long-term import dependency, thereby securing a sustainable energy transition.

Key words: mineral trade; energy transition; mineral and oil prices; economic growth; exchange rates; geopolitics; advanced nations.

GEL Q2, Q21, Q27, Q29

1. Introduction

The worldwide quest for sustainable development goals (SDGs), especially SDG-7 (affordable and clean energy) and SDG-13 (climate action), has established ambitious decarbonization and clean energy targets globally. These scenarios project a rapid, multi-fold expansion in renewable energy infrastructure,

which in turn drives an unprecedented increase in demand for critical minerals [1]. However, the geopolitical phenomena of mineral supply chains marked by high concentration and strategic competition, introduce significant risks. These uncertainties could disrupt these global transition pathways and create a critical gap between climate targets and material feasibility [2]. Within this global context, the role of advanced economies is both pivotal and paradoxical. As leaders in technology, finance, and policy, these nations are setting the most aggressive domestic renewable energy installation targets. Yet, this dependency presents a profound strategic challenge, stemming from a combination of local complexities, such as the growth puzzle of integrating rapid renewable expansion with stable economic performance, and global factors, including volatile raw material pricing, exchange rate fluctuations, and, most critically, geopolitical events [3]. In light of these contexts, our research raises a plausible question:

RQ: How does the mineral import dependency of advanced clean energy economies respond to their energy transition goals as proxied by domestic renewable energy installation capacity, and probing how this relationship is influenced by geopolitical uncertainty.

Although renewable energy is expanding rapidly in advanced economies, a key Issue remains poorly understood: whether the clean energy transition is feasible given the growing reliance on imported critical minerals. Climate policies and energy transition plans often assume that mineral supplies will be easy to access, but in reality, these supply chains are concentrated, exposed to geopolitical risks, and affected by changing economic conditions [3]. As a result, current policies may underestimate the vulnerability of renewable energy growth to disruptions in mineral markets. The available evidence is also scattered. Most research either looks ahead to future demand, focuses on static assessments of critical minerals, or studies mineral trade without directly connecting it to actual growth in renewable energy. This means we do not have a clear picture of how dependence on mineral imports changes with the speed of the energy transition under different market conditions, or how factors like geopolitical risk, price changes, and domestic economic growth affect this relationship. This lack of comprehensive, historical, and distribution-aware evidence is a major gap for policymakers and researchers who want to create strong clean energy strategies in advanced economies.

The research is driven by four intertwined motivations.

Firstly, at the global governance level, there is a pressing need to reconcile ambitious climate targets with material realities. The international commitments enshrined in the Paris Agreement and the SDGs, especially SDG-7, envision a rapid and wholesale transformation of the global energy system [4]. However, this transition is fundamentally material intensive. A systemic understanding is therefore required to assess how physical supply bottlenecks, and concentrated production of critical minerals could delay, derail, or dramatically increase the cost of projected clean energy deployment scenarios [5]. Without such an understanding,

climate policy risks being built upon an untenable material foundation, creating a critical gap between diplomatic ambition and on-the-ground feasibility.

Secondly, the nexus between renewable energy deployment and mineral import demand is not governed by a static or uniform elasticity. Its intensity likely varies depending on both domestic economic indicators, such as growth rates, and foreign indicators, including mineral and oil pricing as well as exchange rates, across diverse macroeconomic conditions [6]. Concurrently, geopolitical events, ranging from trade disputes to regional instability, do not affect all nations or mineral flows symmetrically, creating complex, asymmetric shocks to global supply chains [7]. This asymmetry in the influence of local and global factors necessitates a more granular, conditional analytical approach to understanding the nexus between advanced nations' mineral import dependency and their energy transition pathways.

Thirdly, while existing literature has extensively mapped the material intensity of renewable technologies [8] and highlighted general supply risks [9], a significant empirical gap remains. First, studies often focus on future demand projections or static criticality assessments [10] rather than analyzing historical trade flow responses to actual renewable capacity expansion. Second, there is a paucity of econometric research quantifying how macroeconomic volatilities (price, exchange rates) and geopolitical risks condition this relationship in real-time [11]. Third, studies such as Islam et al. [12] and Islam et al. [13] highlighted the nexus between mineral imports and clean energy, contextualizing it within a framework of local factors like income growth and global factors such as mineral and oil prices and exchange rates. However, these analyses largely overlooked the critical role of geopolitical events. Conversely, more recent work by Mariev & Islam [2] and Islam et al. [12] has integrated geopolitical risks but did so without systematically incorporating the influence of local economic factors, particularly growth. In light of these contexts, our research directly addresses this gap by providing a dynamic, econometric examination of the import-energy transition nexus, moving from theoretical vulnerability and forward-looking scenarios to quantified, historical trade dynamics.

Finally, a core motivation is to model and quantify how the mineral import trajectories of advanced nations evolve under different domestic renewable energy installation scenarios. Unlike some developing economies, advanced nations often lack domestic mineral reserves, coupling their high-tech, service-oriented economies to complex and vulnerable global supply chains [14]. This insufficiency of critical raw materials forces them to rely on imports to achieve a sustainable energy transformation. Although Australia and the USA are among the major mineral importers in the OECD, their renewable energy installation capacity is lower than that of Canada, Spain, and Italy relative to their volumes of mineral imports. Notably, the United Kingdom's renewable energy installation capacity is also low compared to its imported mineral volumes (Figure 1). Analyzing

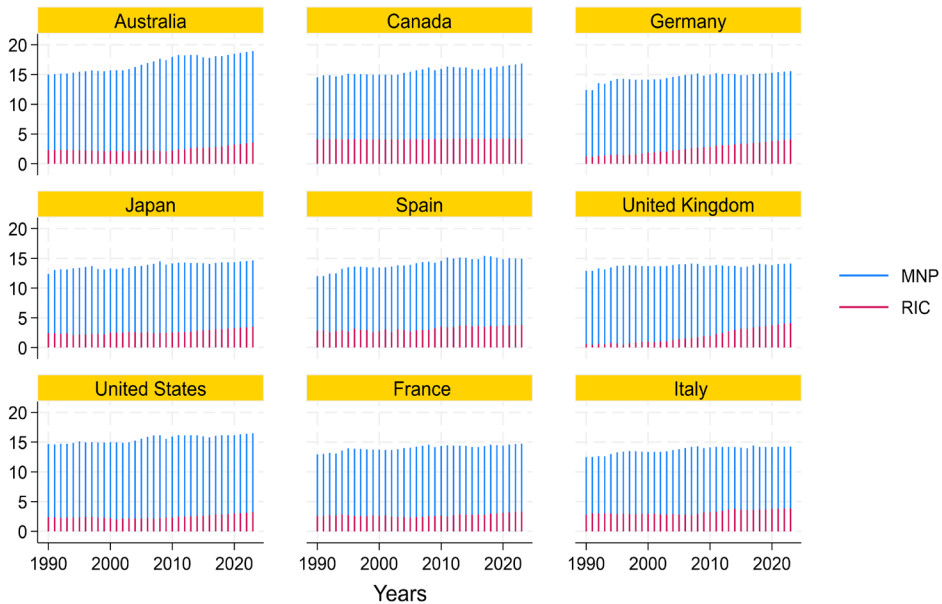


Figure 1. Mineral imports (MNP) and renewable energy installation capacity (RIC) trend (log values) of major renewable energy producing advanced nations during 1990–2023

Sources: Authors' calculation^{1,2}.

such import dependencies under various energy transition pathways is essential for national security and industrial planning.

Based on the motivations above, our study analyzes how advanced nations' mineral imports respond to installed renewable energy capacity from 1990–2023, considering mineral and oil prices, economic growth, and geopolitical risks. To address heterogeneity, we apply the method of moments quantile regression (MMQR) and bootstrap quantile regression (BQR) techniques. Results indicate a positive response of mineral imports to energy transitions across market conditions, strengthening in booming markets. Mineral price effects are regime-dependent: negative in slack markets, aligning with Marshallian demand theory, and positive in booming markets. Oil prices show a complementary effect, while exchange rates exert a negative influence, consistent with the Marshall-Lerner condition. Economic growth stimulates imports, whereas geopolitical risks suppress them. These findings remain robust to tests for spatial dependency, endogeneity, and alternative estimators, including Driscoll-Kraay standard errors (DKSE) and high-dimensional fixed effects (HDFE).

This study makes multiple contributions to the worldwide trade-driven goals of sustainable development for critical minerals, the raw materials of clean energy.

¹ British Geological Survey. <https://www.bgs.ac.uk/mineralsuk/>

² Our World in Data. <https://ourworldindata.org/>

First, it is a pioneering analysis of the clean energy scenarios in major renewable energy-producing advanced nations, examining how their critical mineral imports respond to domestic renewable energy capacity while accounting for national climate commitments.

Second, the research innovatively combines global and local variables within its modeling approach to examine the nexus between mineral import demand and clean energy transformation, both in the presence and absence of geopolitical turmoil.

Third, it develops a theoretical framework that adapts the Heckscher-Ohlin theory of trade to mineral markets shaped by the global clean energy transition, integrating endogenous and exogenous factors such as geopolitical risks. Fourth, it provides a methodological toolkit for selecting econometric techniques based on data characteristics. To address data heterogeneity, the study employs MM-QR and BQR techniques. These techniques quantify the import dependency-energy transition relationship across the entire conditional distribution of mineral trade from slack to booming market scenarios. This can capture heterogeneous effects that mean-based approaches overlook.

Finally, by addressing spatial dependence and endogeneity with DKSE and HDFE methods, the study ensures robust estimations. The resulting insights can offer advanced economies actionable strategies, such as stockpiling, trade diversification, and recycling policies, for designing mineral security plans that are resilient across various future sustainable energy pathways.

This study indents to empirically examine how renewable energy transition, measured by installed renewable energy capacity, affects critical mineral import dependency in major renewable energy producing advanced economies, while accounting for global price dynamics, domestic economic conditions, and geopolitical risks.

Drawing from the theoretical framework and previous research, this study tests four main hypotheses.

H1: Expanding renewable energy positively and significantly affects critical mineral imports in advanced economies.

H2: The size of this effect changes depending on market conditions, showing differences between periods of low and high mineral imports.

H3: Geopolitical risks reduce mineral imports by increasing trade barriers and uncertainty in supply.

H4: Global prices, exchange rates, and economic growth shape the relationship between renewable energy and mineral imports in complex and changing ways.

The remaining sections of the study are organized as follows: Section 2 presents the literature review, including the theoretical framework and relevant empirical studies. Section 3 illustrates the materials and methods. Section 4 describes the empirical findings and discussion. Finally, Section 5 concludes the study with its policy implications.

2. Literature review

2.1. Theoretical framework: The ‘iceberg cost’ of mineral trade in global energy transition

The standard Heckscher-Ohlin (H-O) theorem posits that countries export goods that intensively use their abundant factors of production. For advanced, technology-rich nations with scarce domestic mineral endowments, this implies a structural dependence on imports to fuel a capital-intensive clean energy transition toward sustainable development [15]. However, this frictionless H-O prediction is critically mediated by geopolitical risks (GPRs), which we model as “iceberg trade” costs (τ) [16]. In this formulation, only a fraction τ (where $0 < \tau \leq 1$) of a shipped mineral’s value arrives at its destination; the remainder $(1 - \tau)$ “melts away” due to frictions created by geopolitical instability, creating a wedge between world prices and effective domestic prices.

We consider a two-country (Home H and Foreign F), two-good world, where Home represents a technology-abundant, mineral-scarce advanced economy and Foreign is mineral-abundant. The goods are a critical Mineral good M (land-intensive, with factor share $\alpha > \beta$) and a composite numeraire good C (labor-intensive). Then, Cobb-Douglas technology governs output:

$$M_i = A_{M,i} \cdot T_{M,i}^\alpha \cdot L_{M,i}^{1-\alpha}, \quad C_i = A_{C,i} \cdot T_{C,i}^\beta \cdot L_{C,i}^{1-\beta}, \quad i \in \{H, F\}. \quad (1)$$

Geopolitical risk manifests as an ‘iceberg cost’, τ . If p_w is the world price of M , Home faces an effective import price of $p_f = p_w / \tau$. Quasi-linear utility $U_i = C_i + \ln(M_i)$ generates import demand $M_i^d = 1/p_i$.

This study extends the Heckscher-Ohlin (H-O) model to analyze how geopolitical risk (τ), modeled as an iceberg trade cost, shapes advanced nations’ critical mineral imports during the clean energy transition toward sustainable development. Suppose in a two-country framework (Home: advanced/importer; Foreign: mineral-rich/exporter), the shift toward renewable energy acts as an exogenous demand shock for minerals, intensifying H-O-driven trade.

However, this flow is disrupted by ‘iceberg costs’ where only a fraction τ (where $0 < \tau \leq 1$) of traded value survives geopolitical frictions. This creates a wedge, so home imports at an effective price of $p_f = p_w / \tau$. However, we extend this by integrating additional macroeconomic determinants of import demand into the home country’s demand function. The full specification of mineral imports M_H^d thus becomes:

$$M_H^d = f \left(\underbrace{E}_{\text{Renewable energy capacity}}, \underbrace{p_m, p_o}_{\text{Mineral oil prices}}, \underbrace{EX}_{\text{Exchange rates}}, \underbrace{Y}_{\text{Economic growth}}, \underbrace{\tau}_{\text{Geopolitical risks}} \right), \quad (2)$$

Where, E denotes domestic renewable energy capacity (The primary H-O shock from the pursuit of sustainable development, driving structural import demand); p_m ,

p_o show world mineral and oil prices (Direct input costs affecting import affordability whereas oil prices also influence production and transport costs); EX means exchange rates (It determines the domestic cost of imports (Marshall-Lerner condition)); Y denotes domestic economic growth (Expands general import capacity and industrial demand); τ describes geopolitical risks (Iceberg cost that reduces the effective volume and security of supply, increasing costs).

Therefore, market equilibrium, accounting for these factors and the trade cost, is defined by:

$$M_H - D_H(\tau, p_m, p_o, ex, Y, E) = \tau(D_F - M_F). \quad (3)$$

Moreover, this framework posits that the clean energy transition (E) establishes the baseline mineral trade (import) trajectory under adapted H-O model, while macroeconomic variables (p_m, p_o, ex, Y) and geopolitical risk (τ) determine its feasibility, volume, and stability (Figure 2).

This framework establishes that high risk reduces the exporting country's supply and incentives to export, creating upward price pressure, while simultaneously increasing costs for importers, reducing their demand and creating downward pressure. The net price effect depends on which force dominates. For exports, the direct supply reduction is counteracted by price-driven demand adjustments.

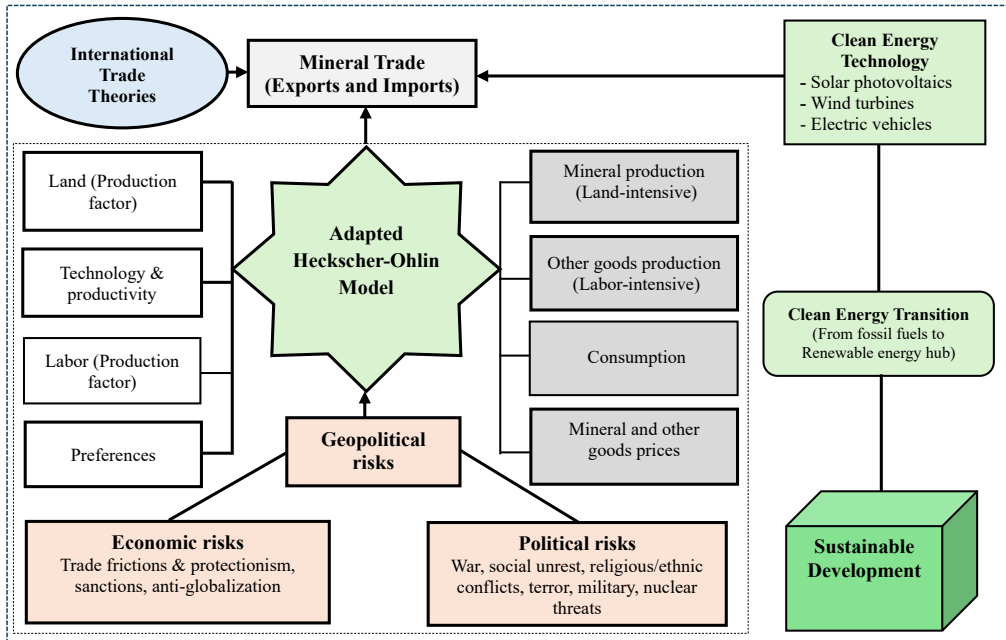


Figure 2. International trade for crucial mineral goods-driven cleaner energy transformation and sustainable development amidst geopolitical risks

Source: Author's construction

If demand adjusts slowly, exports may be sustained, but a sharp price rise will likely overwhelm this, leading to an overall decline in exports. Overall, this theoretical framework provides a comprehensive understanding of how international mineral trade is responsive to sustainable development by enhancing energy transition pathways, amidst the interplay of local and foreign macroeconomic and risk factors, including geopolitical turmoil.

2.2. Empirical works

Empirical studies on the mineral-renewable energy relationship are extensive, yet literature centered explicitly on trade-driven energy transitions remains a developing frontier. Foundational work by Islam et al. [12, 13] addresses this gap, establishing a positive causal link between mineral imports and renewable capacity deployment in OECD nations and major mineral-consuming economies. Their framework is notable for integrating local economic conditions, such as income growth, with global market variables, including mineral prices, oil prices, and exchange rates, demonstrating that these factors exert mixed, context-dependent influences on import dynamics.

A dominant theme across literature is the critical role of price volatility. Research [17] confirms that fluctuations in critical mineral prices directly reshape national investment strategies for clean energy, with distinct effects observed between metal and non-metal mineral categories. This volatility is compounded by geopolitical factors, where export restrictions and inter-state tensions distort trade flows, often creating disproportionate barriers for developing nations seeking to secure essential transition materials [18, 19]. While the macroeconomic impact of mineral price swings is well-documented (e. g., Sánchez-Dávila & Riquelme [20]), their specific transmission mechanism to renewable energy deployment is underscored by Chang et al. [21], who emphasize the mediating role of local resource access. Network analyses further reveal the asymmetric impact of price shocks across different countries, suggesting that stronger regional trade integration could mitigate such risks [22].

The interconnectedness of markets is highlighted in studies of the oil-mineral nexus. Advanced econometric techniques, such as wavelet analysis, reveal complex and often non-linear relationships between oil price shocks and mineral market values, with effects that can be lagged or transient [23]. This interdependence signifies that oil price movements indirectly influence the affordability and security of mineral supply chains, thereby shaping the broader pace of the energy transition [24]. Parallel to this, exchange rate instability is identified as a key determinant of trade patterns, directly affecting the cost structure and reliability of renewable energy supply chains [25].

In addition, the broader literature on mineral trade and economic growth provides essential context, extensively exploring the “resource curse” paradox, dependency, and the destabilizing effects of commodity price shocks [26].

A contemporary shift in this discourse increasingly links growth to sustainable transition pathways, examining how technological innovation and environmental governance might redirect global mineral flows [27]. Within this evolving landscape, the analysis of geopolitical risks has gained prominence, detailing how strategic competition and regional instability can disrupt physical supply routes and trigger market volatility [28].

The reviewed literature above reveals a persistent gap. While initial studies framed the mineral import-renewable energy nexus within local and global economic variables [12, 13], they overlooked geopolitical factors. Later, a crucial work incorporated geopolitical risks [2, 14] but omitted systematic analysis of local economic conditions like growth. However, our study addresses this divide. It provides a dynamic econometric analysis of the import-transition nexus, quantifying historical trade dynamics by integrating both local economic factors and global geopolitical turmoil to explain advanced nations' mineral import responses.

3. Materials and methods

3.2. Data detailing

This research examines how mineral demand in nine advanced economies (Australia, Canada, Germany, Japan, Spain, the United Kingdom, the United States, France, and Italy) responds to their installed renewable energy capacity from 1990 to 2023. The analysis controls the effects of local (economic growth) and global (mineral and oil prices, exchange rates, and geopolitical risks) variables. These nations are selected based on their status as major renewable energy producers among advanced OECD countries, according to the British Geological Survey¹.

The study's dependent variable is the import volume of critical minerals (MNP), specifically copper, nickel, aluminium, and rare earth elements, measured in thousands of metric tons². The primary explanatory variable is renewable energy generation (RIC), defined as the cumulative electricity generation in terawatt-hours (TWh) from renewable sources, including solar, wind, hydropower, bioenergy, geothermal, wave, and tidal energy³. The model also includes control variables for global commodity prices: mineral prices (MRP), calculated as an average price per pound in U.S. dollars for copper, nickel, and aluminium, and global crude oil prices (OLP) in U.S. dollars per barrel. Both the MRP and OLP series are sourced from Macrotrends⁴.

The model incorporates macroeconomic indicators: the real effective exchange rate (EXR, 2010=100) and gross domestic product per capita (GDP, constant 2015 US dollars) as a measure of economic growth. Both the EXR and GDP data are obtained from the World Bank⁵. The final control variable is the Geopolitical Risk

¹ British Geological Survey. <https://www.bgs.ac.uk/mineralsuk/>

² Sourced from British Geological Survey. <https://www.bgs.ac.uk/mineralsuk/>

³ Sourced from Our World in Data. <https://ourworldindata.org/>

⁴ Sourced from Macrotrends. <https://www.macrotrends.net/>

⁵ Sourced from World Bank. <https://clck.ru/3RZZEP>

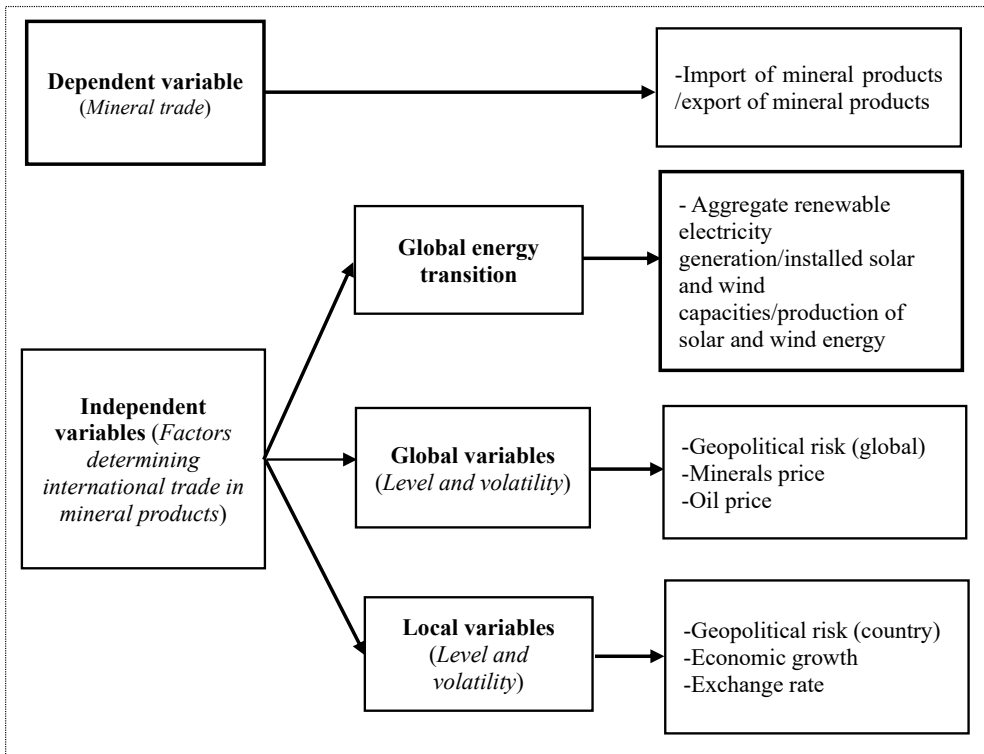


Figure 3. Variable specifications for mineral trade and the global energy transition nexus

Source: Authors’ construction

Index (GPR), developed by Caldara & Iacoviello [29]. This index quantifies geopolitical tensions by measuring the frequency of articles related to geopolitical risk in leading 10 US newspapers. It captures risks associated with wars, terrorism, and tensions between states that could threaten international relations. A higher index value indicates elevated geopolitical instability and vice versa. Notably, the variable specifications are represented in Figure 3.

3.3. Econometric methods selection

For empirical investigation, the choice of econometric methods depends on the characteristics of the data. These may include properties such as normality or non-normality, stationarity or non-stationarity, fat- or thin-tailed distributions, homogeneity or heterogeneity, the presence of endogeneity or reverse causality, and cross-sectional dependence or independence, among others. The selection of an appropriate econometric technique is guided by these features.

While the data used in this study is panel data, we also show time-series data properties to inform the selection of suitable econometric methods from the methodological toolkit presented in Figure 4. Notably, our dataset exhibits heterogeneity, which justifies the use of quantile regression techniques, specifically

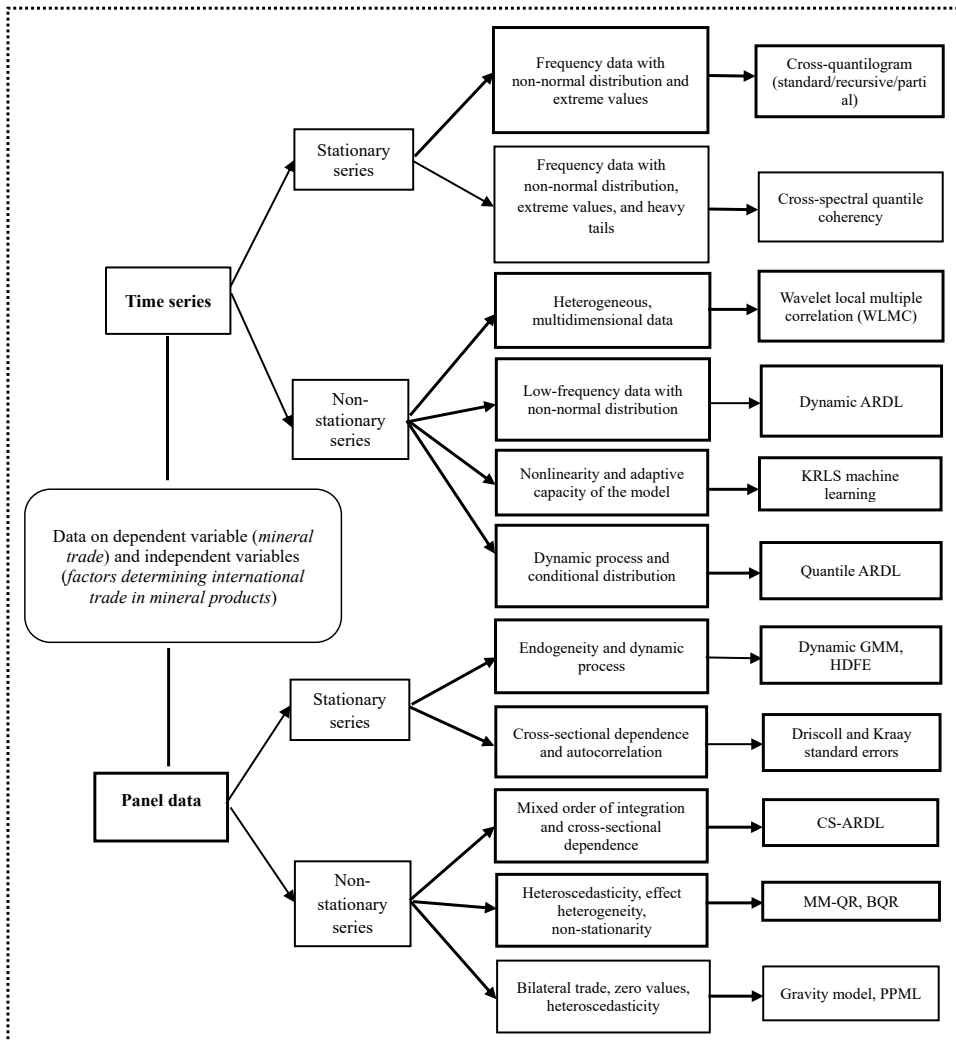


Figure 4. Methodical toolkit for econometric method selection to assess the global energy transition impacts on mineral trade under geopolitical risks

Source: Author's construction

MM-QR and BQR, for empirical testing. In addition, to check for cross-sectional dependency and potential endogeneity, we use the DKSE and HDFE techniques for exploring robust findings.

3.3.1 Method of moments quantile regression (MM-QR) technique

The MM-QR approach, developed by Machado & Silva [30], provides a comprehensive framework for QR that is particularly well-suited for panel data. Its key innovation is to model the conditional quantiles of a location-scale variant of the original data. The method begins by assuming a linear model for the location and scale (variance) of the dependent variable, Y_{it} , as a function of covariates X_{it} :

$Y_{it} = \alpha_i + X'_{it}\beta + (\delta_i + Z'_{it}\gamma)U_{it}$, where α_i and δ_i are individual fixed effects, and U_{it} is an error term. The conditional quantile $Q_Y(\tau/X)$ is then derived as:

$$Q_Y(\tau/X_{it}) = (\alpha_i + \delta_i q(\tau)) + X'_{it}\beta + Z'_{it}\gamma q(\tau), \quad (4)$$

where $q(\tau)$ shows the τ -th quantile of U_{it} .

Estimation proceeds in two stages: first, the parameters of the location and scale functions are estimated via mean regression and a regression on absolute residuals; second, the conditional quantiles are constructed for any τ using the estimated coefficients. This method-of-moments approach provides a parsimonious way to estimate the entire conditional quantile process and its inference across different quantiles, especially for longitudinal data where unobserved heterogeneity is present.

3.3.2 Bootstrap quantile regression (BQR) approach

In contrast to the parametric structure of MM-QR, the bootstrap quantile regression (BQR) developed by Buchinsky [31] is a resampling-based technique designed primarily for robust inference in the face of non-i. i. d. errors and the non-smooth nature of the QR objective function. The standard QR estimator $\hat{\beta}(\tau)$ for quantile τ minimizes the check function:

$$\hat{\beta}(\tau) = \arg \min_{\beta} \sum_{i=1}^n \rho_{\tau}(Y_i - X'_i\beta), \text{ where } \rho_{\tau}(u) = u(\tau - I(u < 0)). \quad (5)$$

Because the asymptotic variance of $\hat{\beta}(\tau)$ depends on the unknown density of the errors at zero, analytical formulas can be unreliable. BQR circumvents this by repeatedly drawing random samples (with replacement) from the original data, recalculating $\hat{\beta}_b(\tau)$ for each bootstrap sample $b = 1, \dots, B$.

The empirical distribution of these bootstrap estimates is then used to construct confidence intervals — for example, the percentile interval $[\hat{\beta}_{(\alpha/2)}^{boot}, \hat{\beta}_{(1-\alpha/2)}^{boot}]$.

Variants like the ‘pairs bootstrap’ or ‘wild bootstrap’ are often employed to better handle heteroskedasticity. BQR is a flexible, non-parametric tool that makes minimal assumptions, making it a widely applicable default for performing valid statistical inference in quantile regression models.

4. Empirical findings

4.1. Descriptive statistics

Table 1 presents descriptive statistics for study’s variables where mineral imports (MNP) average 14.67, showing substantial between-country variation (SD=1.11). Renewable installation capacity (RIC) averages 2.81 with significant cross-country disparity (SD=0.64). The global variables, such as mineral prices (MRP, mean=4.12), oil prices (OLP, mean=3.70), and geopolitical risk (GPR,

mean=4.58), exhibit zero between-country variation as they are common to all nations but fluctuate over time. Finally, exchange rates (EXR, mean=4.59) and GDP (mean=10.50) display moderate heterogeneity both between and within countries. Overall, the pronounced between- and within-country variations across most variables justify employing distributional methods like MM-QR to analyze heterogeneous effects across different market conditions.

Table 1. **Descriptive statistics**

Variable		Mean	Std. dev.	Min	Max	Observations
MNP	Overall	14.6712	1.2883	12.0059	18.9501	N = 306
	Between		1.1132	13.7161	16.9005	n = 9
	Within		0.7446	12.4615	16.7208	T = 34
RIC	Overall	2.8102	0.8379	0.4828	4.2419	N = 306
	Between		0.6356	1.9179	4.1501	n = 9
	Within		0.5845	1.3751	5.0410	T = 34
MRP	Overall	4.1238	0.7261	3.1104	5.4972	N = 306
	Between		0	4.1238	4.1238	n = 9
	Within		0.7261	3.1104	5.4972	T = 34
OLP	Overall	3.7036	0.6504	2.5428	4.7155	N = 306
	Between		0	3.7036	3.7036	n = 9
	Within		0.6504	2.5428	4.7155	T = 34
EXR	Overall	4.5879	0.1351	4.2131	4.9079	N = 306
	Between		0.0938	4.4369	4.7142	n = 9
	Within		0.1019	4.2720	4.9398	T = 34
GDP	Overall	10.5026	0.2503	9.8502	11.0253	N = 306
	Between		0.2302	10.0875	10.8333	n = 9
	Within		0.1240	10.1647	10.6974	T = 34
GPR	Overall	4.5756	0.2841	3.9301	5.1721	N = 306
	Between		0	4.5756	4.5756	n = 9
	Within		0.2841	3.9301	5.1721	T = 34

Notes: Variables are converted into logarithmic form.

Source: author's calculations.

Figure 5 presents the correlation matrix among key variables. Specifically, mineral imports (MNP) show a strong positive correlation with GDP (0.721), indicating that economic growth drives higher mineral demand. Furthermore, MNP has moderate positive correlations with mineral prices (MRP, 0.407) and oil prices (OLP, 0.432), suggesting that global commodity markets influence import levels. Meanwhile, renewable energy capacity (RIC) correlates positively with MNP (0.277), implying that clean energy expansion contributes to mineral imports, though this relationship is less pronounced than that with GDP.

Additionally, MRP and OLP are highly correlated (0.630), reflecting their interconnected market dynamics. In contrast, exchange rates (EXR) display negative correlations with both MNP (-0.334) and RIC (-0.475), aligning with the expectation that currency appreciation can reduce import costs or demand. Notably, geopolitical risk (GPR) shows minimal linear associations with all other variables, suggesting its effects may be nonlinear or conditional. Overall, the absence of severe multicollinearity — with all correlations below 0.73 — supports the inclusion of these variables in subsequent regression analysis without major redundancy concerns.

The distributional plot in Figure 6 illustrates the positive relationship between RIC and MNP, while highlighting notable heterogeneity across countries. The clustering of multi-petal sunflowers around moderate RIC levels (2–3) indicates a common pattern among most observations, yet the presence of isolated single-petal outliers at both extremes reveals substantial national variation. This dispersion

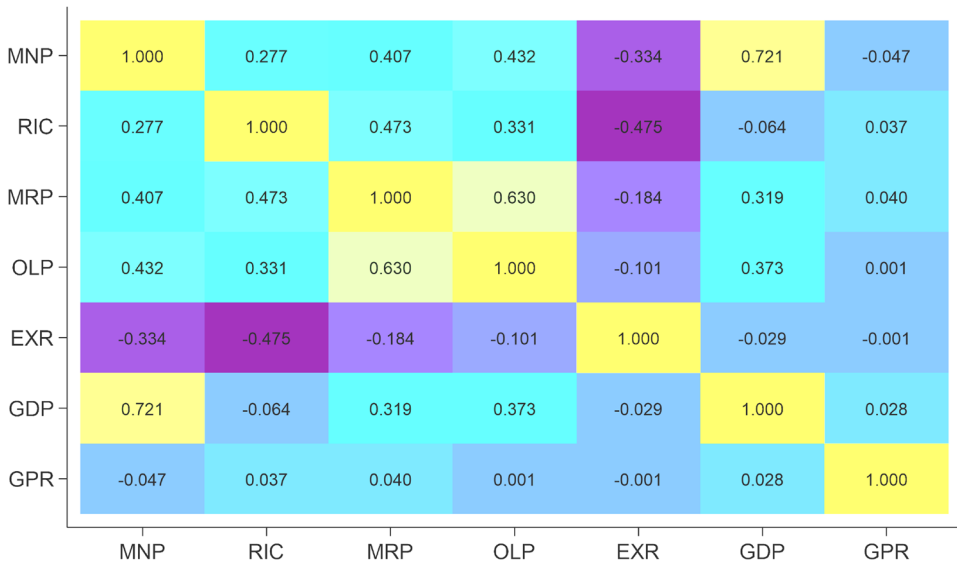


Figure 5. Correlation matrix

Source: author’s calculations.

underscores that the link between renewable expansion and mineral demand is not uniform, justifying the use of distributional methods like MM-QR to capture differing effects across market conditions. Additional sunflower plots for other variables are also available in Figure 6.

Results in Table 2 show strong evidence of slope heterogeneity developed by Pesaran & Yamagata [32] and motivated by Blomquist & Westerlund [33]. All four test statistics are statistically significant at the 1 % level. This indicates that the relationship between the independent variables and mineral imports (MNP) varies significantly across countries. The rejection of the null hypothesis of slope homogeneity justifies the use of estimators like MM-QR that can account for these heterogeneous effects.

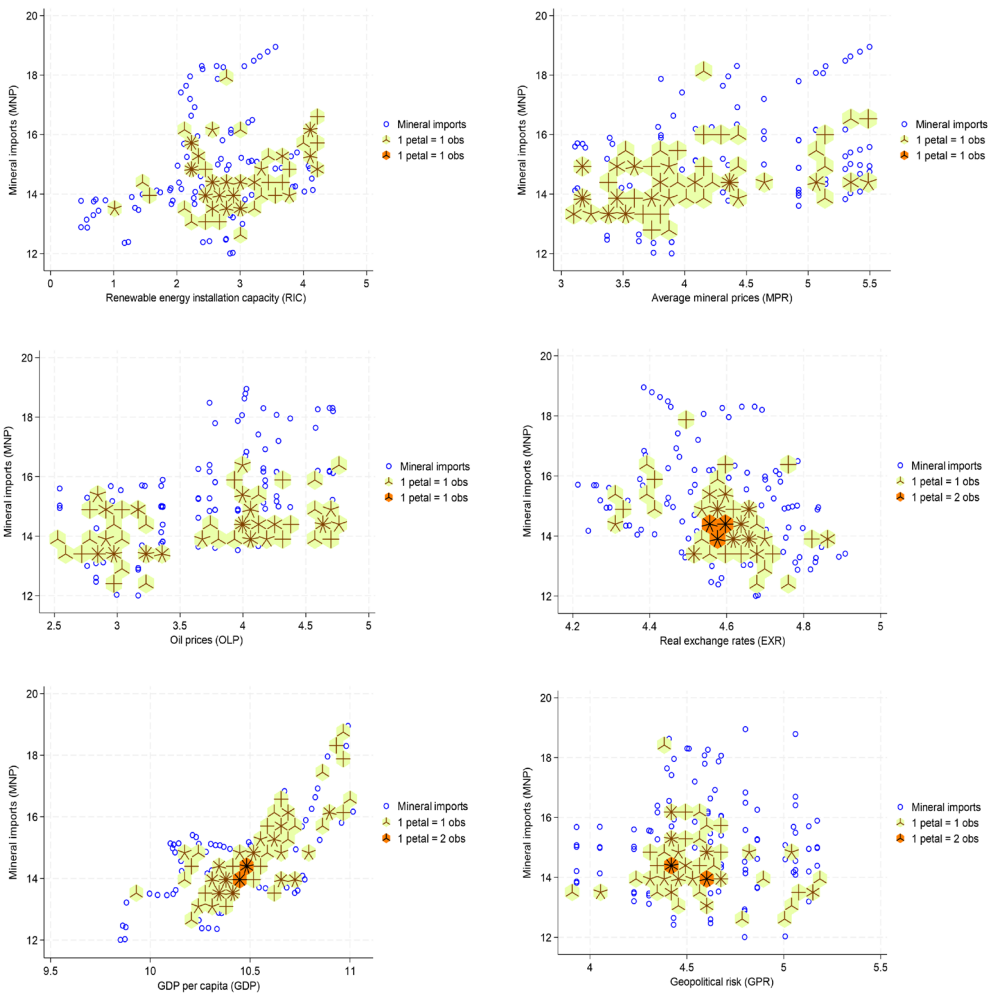


Figure 6. Distributive relationship between the variables

Source: author’s calculations.

Table 2. Slope homogeneity test

Test	Statistics	p-value
Pesaran and Yamagata [32]		
$\tilde{\Delta}$	12.712***	0.000
$\tilde{\Delta}_{adj}$	14.537***	0.000
Blomquist and Westerlund [33]		
$\tilde{\Delta}_{HAC}$	7.817***	0.000
$\tilde{\Delta}_{HAC adj}$	8.939***	0.000

Note: *** denotes 1 % level of significance.

Source: author’s calculations.

Table 3 reveals a strong cross-sectional dependence among the panel units, as the CD tests are statistically significant for MNP, RIC, EXR, and GDP, with notably high average correlations ($\hat{\rho} > 0.86$ for most), thereby indicating substantial interconnectedness across countries. Regarding unit-root properties, the CADF tests confirm that all country-specific variables are non-stationary at levels $I(0)$ but become stationary at first differences $I(1)$, which implies they are integrated of order one. Finally, global variables such as MRP, OLP, and GPR are excluded from these tests since they represent common factors across all panels.

Table 3. CD and panel unit-root (CADF) tests

Variables	CD test		Unit root test	
	Statistics	$\hat{\rho}$	CADF (Level)	CADF (First difference)
MNP	31.42***	0.898	-4.536***	-6.879***
RIC	30.21***	0.864	0.828	-7.841***
MRP	—	—	—	—
OLP	—	—	—	—
EXR	3.89***	0.414	0.319	-6.325***
GDP	30.27***	0.865	1.021	-6.394***
GPR	—	—	—	—

Notes: Asterisks indicate statistical significance at the 1 % level. For the global variables, namely mineral prices (MRP), oil prices (OIP), and geopolitical risks (GPR), cross-sectional dependence (CD) tests and second-generation panel unit-root tests (such as CADF) are not applicable. Columns 2 and 3 report the CD test statistics and average cross-sectional correlations ($\hat{\rho}$), respectively. Columns 4 and 5 present the CADF (Z[t-bar]) test results for level $I(0)$ and first-differenced $I(1)$ specifications, respectively.

Source: author’s calculations.

Table 4. **Westerlund co-integration test**

Statistic	Value	Z-value	p-value
Gt	-3.307***	3.554	0.000
Ga	-16.507***	2.079	0.019
Pt	-9.482***	3.661	0.000
Pa	-15.544***	3.31	0.001

Note: *** denotes the 1 % level of significance.

Source: author's calculations.

Table 4 depicts the Westerlund's [34] co-integration test results. We find that all four test statistics are significant at the 1 % level, indicating strong evidence of a long-run equilibrium relationship among the variables. The significance of both the group-mean statistics (Gt, Ga) and panel statistics (Pt, Pa) suggests that cointegration exists not only for some countries but across the entire panel. This confirms that mineral imports and their determinants share a stable long-run association, validating the use of cointegration-based analysis.

4.2. *Main Findings from the MMQR Technique*

The MMQR analysis of mineral imports across nine advanced renewable energy-producing nations reveals distinct patterns across market conditions. First, we analyze the response of mineral imports to renewable energy capacity while controlling geopolitical risks along with other local (economic growth) and global (mineral prices, oil prices, exchange rates) variables (Table 5). Notably, under the MMQR framework, quantiles q.15–q.50 correspond to slack markets, whereas quantiles q.75–q.95 represent booming market conditions.

Table 5. **Mineral imports and energy transition including geopolitics using the MM-QR method**

Variables	Location	Scale	q.15	q.25	q.50	q.75	q.95
RIC	0.298*** (0.0632)	-0.0248 (0.0417)	0.329*** (0.0706)	0.317*** (0.0630)	0.301*** (0.0622)	0.280*** (0.0770)	0.242* (0.127)
MRP	0.00509 (0.0933)	0.160*** (0.0615)	-0.191* (0.108)	-0.114 (0.0936)	-0.0123 (0.0917)	0.123 (0.115)	0.370** (0.188)
OLP	0.167* (0.0931)	0.111* (0.0614)	0.0308 (0.105)	0.0844 (0.0931)	0.155* (0.0917)	0.249** (0.114)	0.421** (0.187)
EXR	-2.029*** (0.357)	-0.398* (0.235)	-1.541*** (0.403)	-1.733*** (0.356)	-1.986*** (0.351)	-2.323*** (0.436)	-2.938*** (0.717)

End of table 5

Variables	Location	Scale	q.15	q.25	q.50	q.75	q.95
GDP	3.588*** (0.200)	-0.0327 (0.132)	3.628*** (0.224)	3.612*** (0.200)	3.591*** (0.197)	3.564*** (0.244)	3.513*** (0.402)
GPR	-0.333*** (0.121)	-0.0315 (0.0801)	-0.294** (0.136)	-0.310** (0.121)	-0.330*** (0.120)	-0.356** (0.148)	-0.405* (0.244)
Constant	-13.66*** (2.831)	1.853 (1.867)	-15.93*** (3.172)	-15.03*** (2.823)	-13.86*** (2.787)	-12.29*** (3.453)	-9.424* (5.687)
Obs.	306	306	306	306	306	306	306

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: author's calculations.

Table 5 reveals that the response of mineral imports (MNP) to renewable energy installation capacity (RIC) is positive and statistically significant across all quantiles, with coefficients ranging from 0.329 at the 15th quantile to 0.242 at the 95th quantile. This indicates that renewable energy expansion consistently increases mineral imports, though the magnitude of this effect diminishes in booming market conditions.

Table 5 also shows that mineral prices (MRP) exhibit a distinctive pattern on MNP, shifting from a negative impact in slack markets (-0.191 at q.15) to a positive impact in booming markets (0.370 at q.95). This sign reversal in MRP's effect on MNP validates the Marshallian kinked-demand curve in resource economics [16]. During slack market conditions, higher mineral prices reduce mineral imports as price-sensitive buyers defer purchases.

Table 5 also illustrates that oil prices (OLP) demonstrate a complementary effect on MNP that strengthens progressively from slack markets (0.0308 at q.15) to booming markets (0.421 at q.95).

Table 5 shows that exchange rates (EXR) exert a uniformly negative impact on MNP that intensifies from slack markets (-1.541 at q.15) to booming markets (-2.938 at q.95). Table 5 documents that economic growth (GDP) maintains a strong, stable positive influence on mineral imports (MNP) across all quantiles, with coefficients remaining consistently around 3.59 throughout the distribution. Table 5 reveals that geopolitical risks (GPR) exert a persistent negative influence on MNP across all quantiles, ranging from -0.294 at the 15th quantile to -0.405 at the 95th quantile.

Notably, Figure 7 displays the coefficient plot for Table 5, illustrating the graphical trends in the relationship between mineral imports in major renewable energy-producing nations and the other local and global variables.

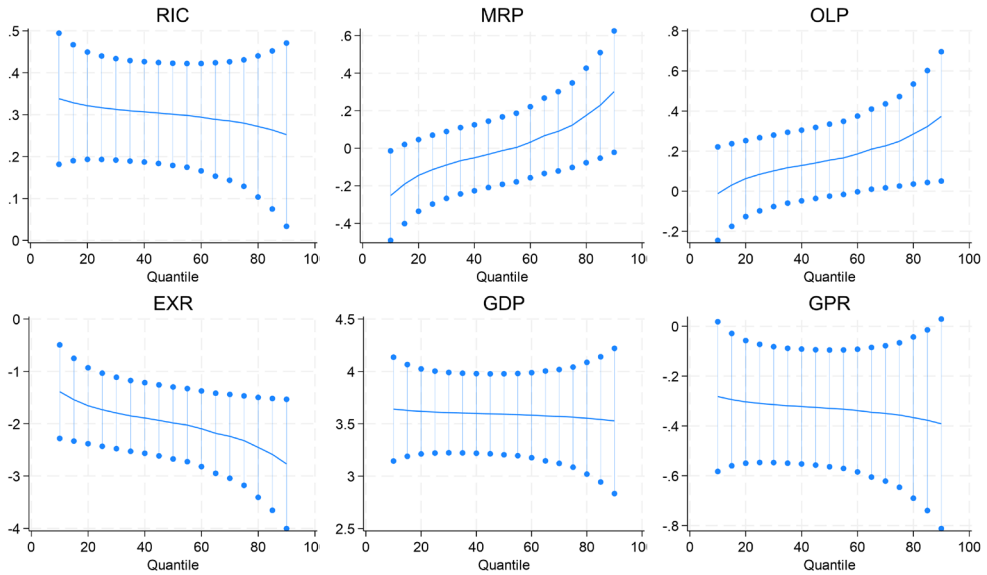


Figure 7. Coefficient plot for Table 5

Source: author's calculations.

Even after excluding geopolitical risks from the model, the findings remain consistent, as shown in Table 6. This suggests that although geopolitical risks independently impede the mineral imports of advanced nations, their exclusion does not materially alter the influence of other local and global variables on import volumes. Notably, the results presented in Table 6 are visually summarized in the coefficient plot shown in Figure 8.

Table 6. Mineral imports and energy transition excluding geopolitics using the MM-QR method

Variable	Location	Scale	q.15	q.25	q.50	q.75	q.95
RIC	0.293*** (0.0640)	-0.0263 (0.0417)	0.324*** (0.0723)	0.313*** (0.0652)	0.296*** (0.0630)	0.273*** (0.0773)	0.234* (0.124)
MRP	-0.000441 (0.0938)	0.155** (0.0611)	-0.187* (0.109)	-0.121 (0.0960)	-0.0191 (0.0922)	0.117 (0.115)	0.343* (0.183)
OLP	0.175* (0.0931)	0.0994 (0.0606)	0.0548 (0.106)	0.0970 (0.0950)	0.163* (0.0917)	0.250** (0.113)	0.396** (0.180)
EXR	-2.047*** (0.362)	-0.411* (0.236)	-1.552*** (0.413)	-1.726*** (0.369)	-1.998*** (0.356)	-2.359*** (0.439)	-2.959*** (0.701)
GDP	3.573*** (0.201)	-0.0362 (0.131)	3.617*** (0.227)	3.602*** (0.205)	3.578*** (0.198)	3.546*** (0.243)	3.493*** (0.388)

End of table 6

Variable	Location	Scale	q.15	q.25	q.50	q.75	q.95
Constant	-14.93***	1.880	-17.20***	-16.40***	-15.16***	-13.51***	-10.76**
	(2.816)	(1.834)	(3.191)	(2.870)	(2.776)	(3.408)	(5.443)
Obs.	306	306	306	306	306	306	306

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Source: author’s calculations.

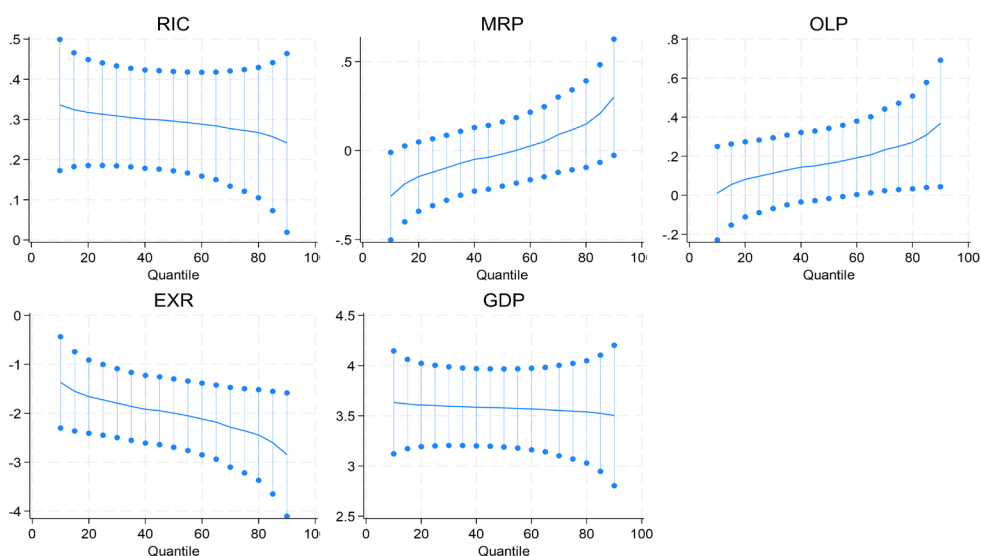


Figure 8. Coefficient plot for Table 6

Source: author’s calculations.

To assess the robustness of our findings from the MMQR analysis, we apply the bootstrap quantile regression technique. The results remain qualitatively identical — while coefficient magnitudes vary slightly across specifications, the signs and significance patterns are consistent, as shown in Tables 7 and 8.

Table 7. Mineral imports and energy transition including geopolitics using the BQR method

Variables (DV: MNP)	q.15	q.25	q.50	q.75	q.95
RIC	0.434**	0.448***	0.303***	0.305***	0.330*
	(0.187)	(0.105)	(0.0541)	(0.0607)	(0.184)
MRP	-0.137	-0.121	0.0488	0.269**	0.259*
	(0.136)	(0.0970)	(0.0831)	(0.111)	(0.148)

End of table 7

Variables (DV: MNP)	q.15	q.25	q.50	q.75	q.95
OLP	0.142 (0.180)	0.136 (0.118)	0.00425 (0.0657)	0.122 (0.116)	0.504** (0.196)
EXR	-1.008 (0.694)	-1.166** (0.516)	-1.900*** (0.270)	-2.254*** (0.248)	-1.915* (1.045)
GDP	3.905*** (0.887)	4.051*** (0.297)	3.633*** (0.161)	2.988*** (0.238)	4.067*** (0.408)
GPR	-0.295* (0.168)	-0.335** (0.136)	-0.332** (0.133)	-0.306** (0.123)	-0.717** (0.292)
Constant	-22.11* (11.33)	-22.65*** (4.580)	-14.40*** (1.985)	-7.001*** (2.293)	-18.54** (8.083)
Observations	306	306	306	306	306

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Source: author's calculations.

Table 8. Mineral imports and energy transition excluding geopolitics using the BQR method

Variables (DV: MNP)	q.15	q.25	q.50	q.75	q.95
RIC	0.379* (0.195)	0.502*** (0.0850)	0.278*** (0.0592)	0.295*** (0.0430)	0.287*** (0.0922)
MRP	-0.0470 (0.107)	-0.132* (0.0729)	-0.0102 (0.0694)	0.252 (0.176)	0.157 (0.165)
OLP	0.00866 (0.144)	0.153* (0.0849)	0.0335 (0.0318)	0.142 (0.107)	0.507*** (0.110)
EXR	-1.229 (0.859)	-0.848* (0.463)	-2.085*** (0.230)	-2.224*** (0.232)	-2.005** (0.836)
GDP	4.082*** (0.532)	4.013*** (0.217)	3.699*** (0.209)	2.944*** (0.215)	3.903*** (0.284)
Constant	-24.03*** (8.432)	-25.44*** (2.030)	-15.54*** (2.263)	-8.044*** (2.431)	-19.14*** (5.836)
Observations	306	306	306	306	306

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Source: author's calculations.

Notably, the tabular results presented in Tables 7 and 8 are visually summarized in Figures 9 and 10, respectively, to validate and illustrate the findings graphically.

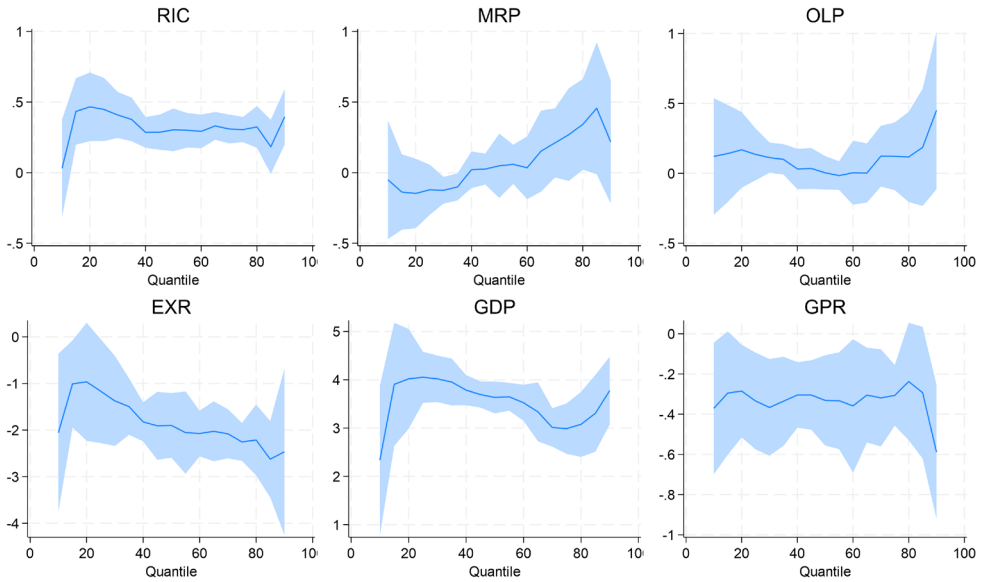


Figure 9. Coefficient plot for Table 7

Source: author’s calculations.

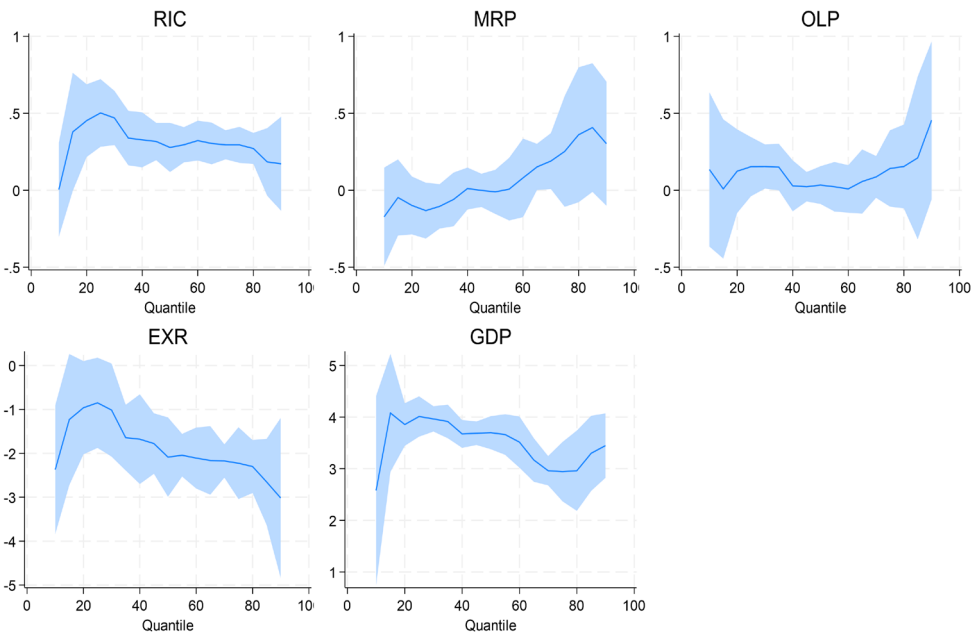


Figure 10. Coefficient plot for Table 8

Source: author’s calculations.

Given the presence of crosssectional dependence and potential endogeneity in the data, we employ DriscollKraay standard errors (DKSE) and highdimensional fixed effects (HDFE) to address these issues. The results obtained with these methods — which align with those from the MMQR and bootstrap quantile regression techniques — provide further robustness checks for our core findings.

Both methods-generated findings in Table 9 consistently show that renewable energy installation capacity (RIC) and economic growth (GDP) have significant positive effects on mineral imports, whereas geopolitical risks (GPR) exert a significant negative influence, confirming their disruptive role in trade. The coefficients for oil prices (OLP) are positive and significant, indicating a complementary relationship, while exchange rates (EXR) show a strong negative impact, aligning with standard trade theory. Notably, mineral prices (MRP) are statistically insignificant across all specifications. The stability of coefficients and R-squared

Table 9. Robust findings from DKSE and HDFE techniques

Variables	DKSE-based findings		HDFE-based findings	
	With GPR	Without GPR	With GPR	Without GPR
RIC	0.298*** (0.0702)	0.293*** (0.0718)	0.298*** (0.0683)	0.293*** (0.0687)
MRP	0.00509* (0.0844)	-0.000441 (0.0952)	0.00509* (0.0836)	-0.000441 (0.0841)
OLP	0.167*** (0.0605)	0.175** (0.0777)	0.167* (0.0882)	0.175** (0.0887)
EXR	-2.029*** (0.288)	-2.047*** (0.294)	-2.029*** (0.364)	-2.047*** (0.366)
GDP	3.588*** (0.153)	3.573*** (0.162)	3.588*** (0.195)	3.573*** (0.196)
GPR	-0.333*** (0.101)		-0.333** (0.151)	
Constant	-13.66*** (2.309)	-14.93*** (2.403)	-13.66*** (2.814)	-14.93*** (2.771)
Observations	306	306	306	306
R-squared	0.668	0.663	0.668	0.663
Numberofgroups	9	9	9	9

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: author's calculations.

values (approximately 0.66–0.67) across both methodologies, irrespective of whether GPR is included, underscores the robustness of these core findings to different treatments of cross-sectional dependence and unobserved heterogeneity.

This scatter plot in Figure 11 examines the relationship between renewable energy capacity and mineral imports among major advanced economies transitioning to clean energy, where the clear positive trend indicates that expanding renewable infrastructure consistently increases demand for critical minerals. Specifically, the United States and Germany show the strongest combination of high renewable capacity and substantial mineral imports, thereby reflecting significant mineral dependency for their energy transitions. In contrast, Australia presents a distinct case as a major mineral producer with only moderate renewable growth, which suggests that its resources largely support other nations' transitions rather than its own. Meanwhile, Japan maintains considerable renewable capacity with relatively lower mineral imports, potentially indicating more efficient use or alternative sourcing strategies.

Additionally, other nations including the United Kingdom, Italy, France, Spain, and Canada follow the general trend at varying levels, thus revealing distinct national approaches to securing mineral supplies amid clean energy expansion. Notably, the pairwise relationship between variables is presented in a graphical representation based on linear regression in Figure 12.

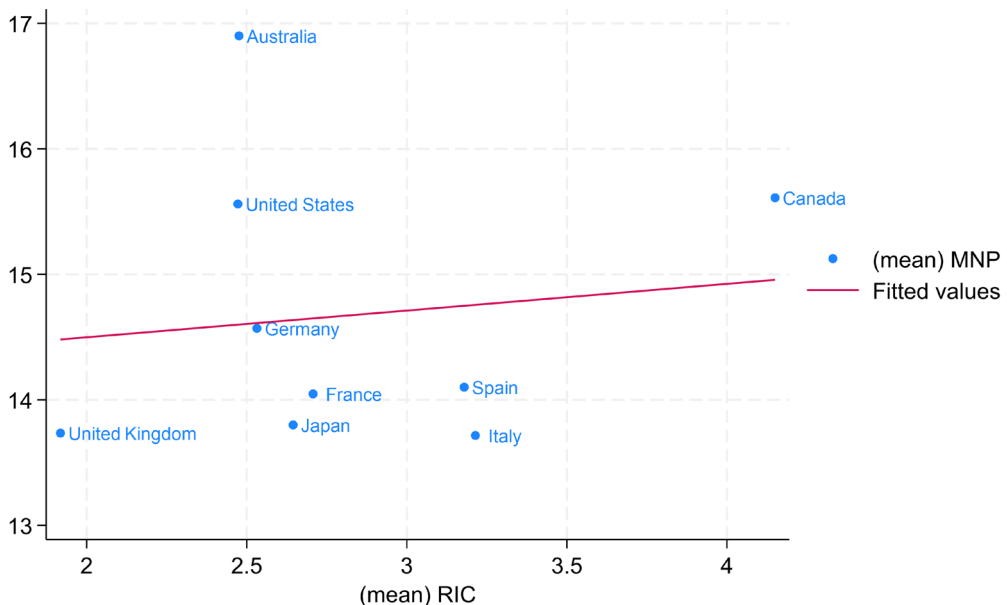
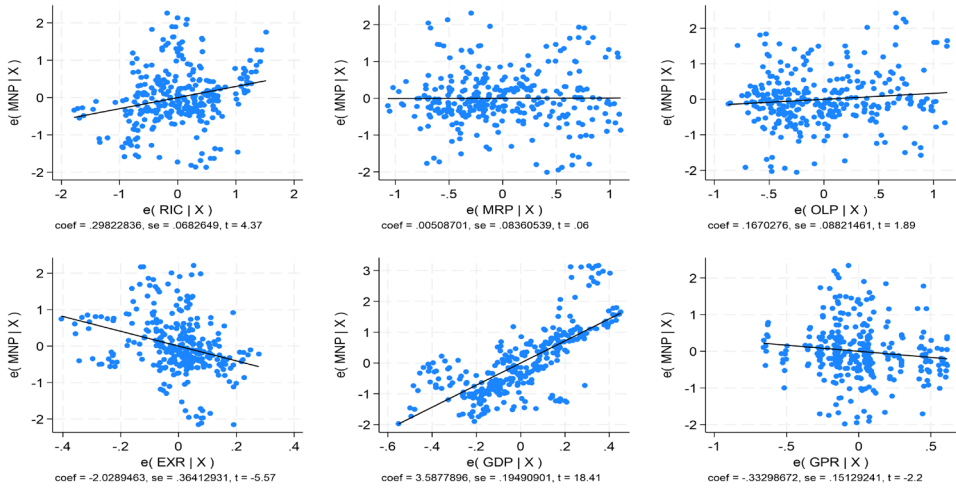


Figure 11. Scatterplot for mineral imports and renewable energy installation capacity

Source: author's calculations.

Panel A: Mineral imports and clean energy nexus including geopolitics



Panel B: Mineral imports and clean energy nexus excluding geopolitics

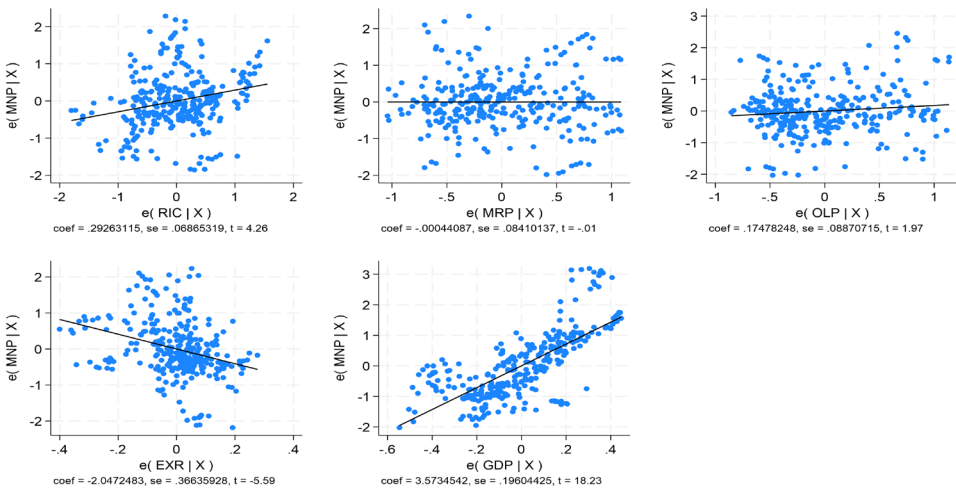


Figure 12. Linear regression graphical representation

Source: author’s calculations.

5. Discussion

5.1. Confirmation of the research hypotheses

This study aims to investigate whether in advanced economies the expansion of a renewable energy demand fosters critical mineral import dependence. This relationship is contingent on market states and geopolitical risks.

The empirical evidence highly supports the first hypothesis (*H1*). For all quartiles and estimation methods, capacity of renewable installation is found to have a positive coefficient that is statistically significant concerning mineral imports.

This result suggests that the clean energy transition in advanced economies is intrinsically import-intensive, because of renewable technology's high material intensiveness.

The second hypothesis (*H2*), which posits heterogeneous effects across market conditions, is also supported. The magnitude of the renewable energy–mineral import relationship varies systematically across the conditional distribution of mineral imports, with stronger effects observed in lower and middle quantiles and a moderation in booming market conditions. This pattern suggests that while renewable deployment consistently raises mineral demand, efficiency gains, learning effects, and strategic inventory behavior may dampen marginal import growth during high-demand phases.

The findings further support hypothesis (*H3*) by showing that mineral imports are negatively impacted by geopolitical concerns in all quantiles. The idea that supply chain dependability is hampered by trade friction due to geopolitical instability, independent of market conditions, is supported by this research.

Lastly, the observed nonlinear and state-dependent impacts of mineral prices, oil prices, currency rates, and economic development justify hypothesis (*H4*), highlighting the need of considering macroeconomic and geopolitical conditioning variables when examining the dynamics of mineral trade.

5.2. Comparison with existing literature

The positive relationship between RIC and MNP aligns with material intensity theory Valero et al. [35], which establishes that renewable energy technologies require substantially more minerals per unit of energy generated than fossil fuel alternatives. The decreasing marginal effect across quantiles reflects capacity-saturation and learning-by-doing dynamics Kittner et al. [36], where initial renewable deployment creates steep mineral demand for MNP, but subsequent efficiency gains and technological improvements gradually reduce mineral requirements per additional capacity unit.

From the practical perspective, during slack markets (lower quantiles), nations like Germany and the United States successfully utilized green stimulus packages to simultaneously boost renewable capacity and mineral imports [37]. This demonstrates how clean energy investments can drive MNP as Part of counter-cyclical recovery strategies. In booming markets (upper quantiles), the relatively weaker effect on MNP necessitates policy shifts toward supply-chain resilience, exemplified by Japan's Critical Minerals Security Partnership [38] and Australia's strategic stockpiling initiatives [39] that specifically target securing mineral imports during high-growth periods.

In booming conditions, inelastic speculative demand dominates where higher prices signal scarcity and trigger competitive stockpiling, paradoxically increasing mineral imports despite higher costs. In slack markets during the 2015–16 commodity downturn, price-based instruments effectively moderated mineral imports in price-sensitive

nations like Italy and Spain [40]. In booming markets, however, these same tools became counterproductive during the 2021–22 price surge, when the United States, Japan, and Germany responded by accelerating strategic stockpiling, increasing their mineral imports through long-term contracts despite rising prices [41]. This necessitates state-contingent pricing policies for managing mineral imports.

Findings support the short-term complementarity paradox between oil and renewable energy systems [42]. Higher oil prices accelerate renewable energy adoption, which in turn increases mineral imports because renewable infrastructure requires substantial mineral inputs. This relationship explains how oil market dynamics indirectly drive mineral import patterns through energy transition channels. However, during the 2020 oil-price collapse (slack market conditions), the weak oil-mineral import link reflected stalled renewable investment across advanced nations [26]. Conversely, in the 2021–22 oil-price rally (booming market conditions), countries like Japan and Germany responded to higher oil prices by fast-tracking renewable projects, which subsequently increased their mineral import requirements [43]. This pattern underscores how oil price volatility transmits to mineral import volumes through clean energy investment decisions.

Findings also confirm the augmented Marshall–Lerner condition for critical minerals [44]. Currency appreciation reduces mineral imports by increasing their domestic currency costs, with this effect amplifying during economic booms due to precautionary inventory adjustments. Here importers respond to favorable exchange rates by increasing strategic stockpiling when supply-security concerns are heightened. Practically, in slack markets, currency appreciation provided moderate cost relief for mineral imports without significantly altering procurement strategies. In booming markets, however, strong currencies enabled aggressive stockpiling behavior, as countries raced to secure critical mineral supplies amid supply-chain anxieties — demonstrating how exchange rate movements can either constrain or facilitate mineral import strategies depending on market conditions [45].

Results also reflect scale-driven demand theory in resource economics [46]. Economic expansion increases industrial production, infrastructure investment, and consumer demand for technology-intensive goods, all of which raise mineral import requirements proportionally to economic activity. In addition, in both slack and booming markets, GDP growth consistently drives mineral imports across all these nine advanced nations. Growth-oriented stimulus packages directly boosted mineral imports as an integral component of economic recovery efforts during downturns, while sustained economic growth maintained continuous upward pressure on mineral imports during expansions [47]. This highlights the fundamental link between economic activity and mineral import volumes.

Outcomes also highlight supply-chain vulnerability theory in critical mineral markets [48]. Mineral import channels exhibit structural fragility due to extreme geographic concentration of production, making imports uniformly sensitive to geopolitical disruptions regardless of market conditions. Furthermore, the

consistent negative impact aligns with iceberg cost theory [16], where geopolitical risks create “melting” transaction costs that reduce the effective volume of trade. These hidden costs, including increased insurance premiums, compliance with sanctions, enhanced due diligence, and political risk insurance, act as iceberg costs that “melt away” potential trade volumes, making mineral imports less viable despite apparent price advantages

From the practical viewpoints, geopolitical tensions consistently reduce mineral imports across all market conditions, disrupting logistics and financing in slack markets while triggering competitive hoarding and export restrictions in booming markets. The iceberg costs manifest practically through increased lead times, higher compliance burdens, and risk premiums that make mineral procurement economically unfeasible [19]. For example, U.S.-China trade tensions added approximately 15–25 % in hidden compliance costs to rare earth imports, while EU sanctions on Russian commodities created logistical iceberg costs through mandatory certification and rerouting requirements [49]. This persistent vulnerability explains why advanced nations are pursuing comprehensive strategies, including supply chain mapping, political risk insurance pools, and diplomatic trade corridors, to reduce these iceberg costs and secure mineral import channels against geopolitical disruptions through diversification, domestic capability building, and real-time monitoring systems.

5.3. Limitations of the study

There are multiple limitations in this study.

First, this study looks at total mineral imports and not the supply chains of individual minerals. Therefore, some of the differences between minerals in terms of strategic importance and substitutability will not be captured by just looking at total imports of all minerals together.

Second, this study uses an aggregate measure of geographical risk from an accepted index; however, this ignores specific geographical risk and the geographical risk to a source country or bilateral agreement.

Third, this study focuses exclusively on developed countries, and the results may not be applied to developing or resource-rich countries having different production structures.

Finally, although using a quantile regression allows for identifying heterogeneity, the results are still only observational and do not establish a causal mechanism. As a result, further research can build upon the framework of this study by adding in bilateral trade data, mineral-specific analysis, and firm-level procurement behaviours.

6. Conclusion and policy implications

This study demonstrates that the clean energy transition in advanced economies is fundamentally intertwined with global critical mineral markets. Building on the theoretical underpinnings of iceberg-type trade costs and a methodical toolkit

for econometric method selection, we employ MM-QR as our primary analytical approach, a choice driven by the specific features of our dataset. The results reveal a robust and consistently positive relationship between renewable energy capacity installation and mineral import dependency across all market conditions, from slack to booming.

This finding confirms that building clean energy infrastructure is inherently import-intensive for these resource-constrained advanced nations. The analysis further reveals that the drivers of mineral import demand are not uniform but are contingent on market states. Mineral prices exhibit non-linear effects, exerting a traditional negative influence in slacking markets but a positive one during booming conditions. This suggests that in periods of high demand, security-of-supply concerns override price sensitivity. Oil prices act as a complement to mineral imports, indicating that broader energy costs and potential input substitutions shape import decisions. The negative impact of domestic currency depreciation aligns with the Marshall-Lerner condition from standard trade theory, while economic growth predictably fuels import demand.

Most crucially, the study identifies geopolitical risks as a significant impediment to mineral trade flows, directly threatening the stability of clean energy supply chains. However, the robustness of these findings is confirmed through supplementary analyses using the BQR method. Furthermore, the DKSE and HDFE techniques are employed to account for spatial dependency and potential endogeneity within the dataset, respectively.

Based on our findings, the policy implications must extend beyond conventional supply chain measures to incorporate a critical understanding of market-state dynamics and geopolitical risk into the very architecture of energy and trade policy.

1. Given that import demand is price-inelastic during booming market conditions, strategic stockpiling programs should be activated and funded counter-cyclically. Governments should accumulate reserves during slack market periods when prices are lower and supply is more plentiful, creating a vital buffer to be deployed during boom phases. This approach would mitigate the cost and scramble for materials when demand surges, thereby enhancing energy security and providing market stability.

2. The need for resilient institutional frameworks must evolve into the creation of a “critical minerals club” among allied advanced and resource-rich economies. This club would not only standardize regulations and ensure crisis-era trade flows but would also establish a shared, transparent system for environmental and labor standards. Such a platform could facilitate joint investments in processing infrastructure in partner nations, co-funding for recycling innovation hubs, and the development of a collective early-warning system for geopolitical and logistical disruptions, turning ad-hoc diplomacy into structured, operational cooperation.

3. The acceleration of innovation must be strategically targeted. Public R&D funding and tax incentives should be explicitly prioritized for technologies that

show the highest potential to decouple renewable energy growth from primary mineral demand. This includes not only recycling but also design-for-disassembly in wind turbines and solar panels, and alternative chemistries for batteries, such as sodium-ion, that utilize more abundant materials.

4. Integrating mineral security requires a formal “mineral stress test” for national energy transition plans. Similar to financial sector stress tests, these assessments would model the vulnerability of deployment targets to potential supply shocks, price volatility, and geopolitical events, forcing a realistic alignment between ambitions and material availability.

5. Fostering domestic capacities must be pursued with a clear-eyed focus on strategic autonomy in specific, value-added segments rather than futile attempts at full self-sufficiency. Policy should identify and support domestic champions in high-purity refining, component manufacturing, and advanced material recovery from e-waste, ensuring that the nation retains key technological and industrial competencies within its borders. In essence, the path forward requires a sophisticated, multi-pronged strategy that is as dynamic and interconnected as the mineral-energy nexus itself, ensuring that the clean energy transition is both rapid and resilient for sustainable development.

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Международная торговля критически важными минеральными ресурсами и глобальный энергетический переход: количественная оценка взаимосвязи для стран с развитой чистой энергетикой

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Аннотация. Глобальное расширение использования систем чистой энергии значительно увеличило спрос развитых стран на критически важные минеральные ресурсы, вызывая опасения по поводу торговой зависимости и безопасности поставок. В данном исследовании рассматривается, как установленная мощность возобновляемой энергии влияет на зависимость от импорта критически важных минералов в девяти крупнейших развитых странах — производителях возобновляемой энергии в период с 1990 по 2023 г., с учетом цен на минералы и нефть, валютных курсов, экономического роста и геополитических рисков. Для учета гетерогенных эффектов в зависимости от рыночных условий в исследовании используется метод моментов квантильной регрессии (MM-QR). Результаты показывают стабильно положительную и статистически значимую связь между мощностями возобновляемой энергии и импортом минералов во всех квантилях, подтверждая импортотемкий характер перехода к чистой энергетике. Этот эффект наиболее силен в нижних квантилях (в условиях небольшого импорта) и ослабевает во время бумов импорта. Цены на минеральные ресурсы демонстрируют эффекты, зависящие от режима, отрицательно влияя на импорт на вялых рынках, но показывая положительную взаимосвязь в условиях подъема. Цены на нефть демонстрируют комплементарный эффект, в то время как валютные курсы оказывают негативное влияние, что согласуется с теорией торговли. Экономический рост активно стимулирует импортный спрос, тогда как геополитические риски постоянно подавляют потоки торговли минеральными ресурсами во всех состояниях рынка (квантилях). Полученные результаты продемонстрировали робастность при оценивании с помощью бутстрап-квантильной регрессии, моделей со стандартными ошибками Дрисколла — Краая и многомерными фиксированными эффектами. Теоретическая значимость исследования состоит в модификации модели Хекшера — Олина путем интеграции геополитического риска. Инструменты повышения устойчивости торговли минеральными ресурсами должны включать в себя формирование стратегических запасов, направленных на противодействие циклическим колебаниям рынка, диверсификацию источников поставок и сотрудничество с партнерами в рамках «клуба критически важных минералов» для смягчения геополитических рисков, а также ускорение инноваций в области эффективности использования материалов и переработки отходов для существенного снижения долгосрочной зависимости от импорта и обеспечения устойчивого энергетического перехода.

Ключевые слова: торговля минеральными ресурсами; энергетический переход; цены на минералы и нефть; экономический рост; валютные курсы; геополитика; развитые страны.

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