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ORIGINAL PAPER

How do strategic mineral resources affect clean energy transition? Cross-sectional autoregressive distributed lag (CS-ARDL) approach

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Abstract

In the transition to a low carbon economy, minerals are crucial. The demand for the minerals required to create and install green energy technology, such as solar panels, wind turbines, electric vehicles, and energy storage, is rising along with it. In particular, the countries that hold these mineral reserves should be thought of as thriving economically from the rising demand for essential mineral resources (such as cobalt, lithium, and others). This study uses import demand function analysis to look at how the major mineral importing countries' mineral import demand changed in response to the clean energy transitions between 2000 and 2021 for selected 14 countries. In the study, the cross-sectional autoregressive distributed lag (CS-ARDL) method was used. Findings show that long-term renewable energy production has a largely favorable impact on mineral import demand. Additionally, CO_2 emissions have a long-term negative impact on mineral import demands, but energy intensity and exchange rate are favorable for mineral imports. The findings have significant ramifications for using the mineral trade to speed up the transition to sustainable energy around the world. Therefore, the study's key proposed policy is to emphasize the value of mineral resources in clean energy while maximizing their use in the transition to carbon-free energy.

Keywords Mineral resources · Clean energy transition · Renewable energy · Demand analysis · ARDL approach

Introduction

The existing energy system is heavily built on fossil fuels, including both technology and storage infrastructure. Therefore, countries set net zero carbon targets to avoid catastrophic climate change as a result of the Paris Agreement, which was signed in 2015. To achieve the established net zero carbon target and meet their energy demand, countries must create significantly varied systems based on renewable energy (RE) sources (Figueres et al. 2017). The production and maintenance of RE technologies and electric vehicles (EV) require the flow and stock of mineral resources (lithium, nickel, cobalt, manganese, etc.). In other words, mineral reserves are of great importance in the transition to a low-carbon energy system (Calvo and Valero 2022; Toro et al. 2020; Vidal 2017; Ali et al. 2017). Minerals are used to generate and sustain energy conversion technologies in the clean energy transition from fossil fuel-based energy sources to RE sources (Moreau et al. 2019).

Today, the strategic importance of vital minerals is still emphasized, and their competitiveness is getting more intense due to the intensity of trade conflicts and uncertainty in the international arena (Zhu et al. 2022; Huang et al. 2021). Additionally, the COVID-19 pandemic, which affected the entire world in 2020, has caused and is currently causing the possible risk of disruption in the supply chains of essential minerals, which in this case hinders the clean energy transition process (Giese 2022; Zhu et al. 2021; Kim and Karpinski 2020; Chadha 2020). Hence, a country's position in the key mineral trade network depends on its control and influence over these essential minerals, which are crucial to the growth of RE sources (Zhu et al. 2022; Xi et al. 2019). Critical minerals can have different effects on the development of RE industries.

The main motivation for this paper is to reveal the contribution of minerals, which have an important place in the use of RE, to the CO_2 emission target. Major mineral-importing countries also support the global carbon target (which

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aims to keep the rise in average temperature under 1.5 °C) (Calvo and Valero 2022). Countries must adopt the usage of RE sources and electric vehicles to fulfill their objectives. Following motivation of the study is that a lot of raw material is required for RE technologies. Many authors have drawn attention to how to access critical minerals required for RE generation, distribution, or storage technology (Vakulchuk et al. 2020; Mills 2020; Habib et al. 2016). For instance, a solar power plant needs four tons of copper to produce one megawatt of installed capacity, and also photovoltaic cells include copper-indiumgallium-selenide alloy (CIGS) or cadmium-tellurium (CdTe) and silver (Bleiwas 2010). Furthermore, electric vehicles often use lithium, cobalt, or nickel for batteries (Chitre et al.2020). Hence, the main driver of growth in the EV market is maintaining stable and reliable access to mineral resources (Ballinger et al. 2019). As can be seen, mineral resources are crucial for countries that want to convert to clean energy sources and produce RE. The final motivation of the present study is that the mineral demands in the clean energy transition process have been drawn attention in the literature, and the need for some critical minerals especially in the deployment of RE use has been emphasized (Islam et al. 2022b; Zhu et al. 2022; Gielen 2021; Liang et al. 2022; Klimenko et al. 2021; Ren et al. 2021; Toro et al. 2020; Månberger and Stenqvist 2018; McLellan et al. 2016; Viebahn et al. 2015; Moss et al.2013). It is anticipated that demand would rise significantly for the metals lithium, cobalt, rare earth elements, and graphite, which are particularly necessary for the manufacture of batteries. There will be a seven-fold rise in demand for lithium-ion batteries by 2025 and an 11–13 times increase by 2030 (Dolganova et al. 2020; Küpper et al. 2018). The literature will be improved by exploring minerals, which play a significant role in the shift to sustainable energy.

Based on the aforementioned motivational disclosure, the present paper aims to investigate the response of total mineral import demands to clean energy transitions (capacity of RE) within the context of external determinants (energy intensity, fuel import, economic growth, exchange rate, CO_2 emission, and foreign direct investment) in the context of important mineral importing countries between 2000 and 2021. To CO_2 emission goals, specific country policies relating to mineral resources are also looked at. As a result, the paper promotes collaboration within three distinct fields, which are environment, energy, and mining economics.

The contribution of the paper is the many folds. First, import demand function analysis is used to examine how mineral import demands respond to clean energy transitions. This is the first attempt made by using data, a certain time interval, and selecting 14 countries. Second, unlike earlier research, this study considers major mineral importing countries to anticipate how imported minerals will react to clean energy transitions, such as installed RE capacity under various external dynamics, including RE capacity fuel import, foreign direct investment, economic growth, exchange rate, CO_2 emission, and energy intensity by using CS-ARDL approach. Third, the results of this study, which show how minerals affect the growth of RE, will help us better comprehend the relationship between clean energy transition and minerals. By empirically studying the relationship between key minerals and the clean energy transition, this study creates a fresh contribution to the field. The sample countries, the data used, and the analysis method are all different in this study as compared to earlier studies. Fourth, the present paper also attempts to formulate a sustainable development policy objective in light of the energy and environmental regulations in place in 14 mineral-importing countries. This policy framework is intended to be created by considering how mineral resources have shaped the relationship between RE and climate change. Finally, a clean energy transition may lower the usage of fossil fuels, but it also tends to increase the use of non-fuel essential minerals in supply chains. This creates new dependencies and introduces new scarcity scenarios. Therefore, it is crucial that policy-makers address this condition when developing policies for the demand for critical minerals. Herein lies the study's contribution at the level of policy.

The remainder of the present paper is structured as follows. A review of the available literature on strategic mineral resources is provided in "Literature review." The study's methodology is described in depth in "Materials and methods" and "Empirical findings" presents the empirical findings and is discussed in the literature. The study's final section ends with conclusions and political implications.

Literature review

The overall global mineral demand is anticipated to exceed 40% for copper and rare earth elements, 60–70% for nickel and cobalt, and over 90% for lithium within the context of the Paris Agreement in the next 20 years (Mróz 2022). Lithium is now the most widely used material in electric vehicles and battery storage (Diouf and Pode 2015). As part of the energy transition, the rapid implementation of clean energy technology will result in a considerable increase in mineral demand (Lee et al. 2020). Figure 1 shows the minerals used in RE technology.

When studies on minerals are evaluated in the literature, some studies forecast the future mineral requirements from the perspectives of several countries and the rest of the world (Wang et al. 2022; Galos et al. 2021; Hu et al. 2021; Wen et al. 2019; Beylot et al. 2019; Meinert et al. 2016). Some research has focused on addressing risk scenarios for highly

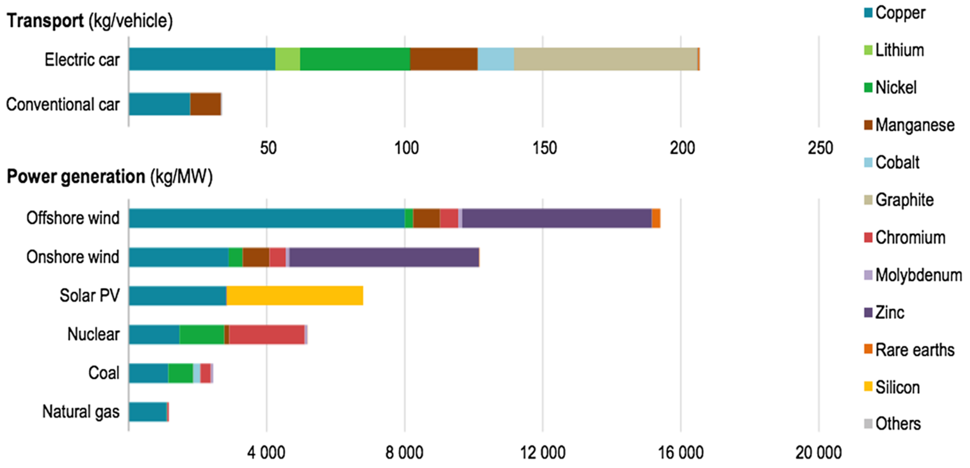

Fig. 1 Minerals used in selected clean energy technologies. Source: IEA (2021). Notes: kg kilogram, MW megawatt. Steel and aluminum

used minerals in the clean energy transition (Nate et al. 2021; Krane and Idel 2021; Church and Crawford 2020; Capellán-Pérez et al. 2019; Watari et al. 2019). According to some studies, the concentration of natural resource reserves in a few key locations could lead to bottlenecks in the process of using minerals to produce sustainable energy (Calvo and Valero 2022; Bazilian 2018; Grosjean et al. 2012). The literature has generally considered studies on the impact of mineral resources on energy or clean energy transitions as theoretical or reviewed. Empirical research on this topic is scarce, and Table 6 in the "Appendix" section also gives specific details on a recent empirical literature review on the linkage between minerals and clean energy.

According to the literature, the demand for this resource on the global market is rising as a result of the mineral consumption flow of countries that produce sustainable energy. In light of this, the hypothesis that "clean energy transitions boost the import demands of minerals on the global market" starts to take shape.

To sum up, earlier researchers examined scenarios for present mineral reserves, mineral use, and the significance of minerals in the switch to clean energy. Environmental concerns including ecological footprint, low-carbon earth, and mineral exploitation have been linked in several studies. To our knowledge, no studies have looked at the response of essential minerals, such as the capacities of RE installation to clean energy transitions.

Materials and methods

Data

This study investigates the responsiveness of mineral import demands to clean energy transitions in the context of China, the USA, Japan, India, South Korea, the Netherlands, Germany, Italy, the UK, Turkey, Russia, Australia, Canada, and South Africa, which import the most minerals. Depending on the data availability of selected countries, the data range is limited from 2000 to 2021. The variables used for analysis, as well as their definition, units of measurement, and sources are presented in Table 1.

To examine the impact of renewable energy capacity (REC), fuel imports (FI), energy intensity (EI), foreign direct investment (FDI), economic growth (GDP), the exchange rate (EX), and CO_2 emissions (CO_2) on mineral

Table 1 Description of the variables used for analysis

Variables	Definition	Unit of measurement	Sources
Dependent variable			
MSI	Mineral sources import	US$ thousand	World Bank & MineralsUK
Independent variables			
REC	Renewable energy capacity	Cumulative, in MW	IRENA
FI	Fuel imports	% of merchandise imports	World Bank
EI	Energy intensity	Koe/$15p	World Bank
FDI	Foreign direct investment	BoP, current US$	World Bank
GDP	Gross domestic product	Current US$	World Bank
EXR	Exchange rate index	2010 = 100	World Bank
CO_2	Carbon emission	Tons per capita	European Commission

Table 2 The homogeneity of slope test inquiry findings

	Statistics	*p*-values
$\widetilde{\Delta}$	3.191***	0.001
$\widetilde{\Delta}_{adj}$	4.151***	0.000
Δ_{HAC}	2.023**	0.043
Δ_{HACadj}	2.632***	0.008

The asterisks ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively

resource import (MSI) by the control variable in the theoretical framework, the following econometric model is used:

$$\mathrm{MSI} = f\,(\mathrm{REC}, \mathrm{FI}, \mathrm{EI}, \mathrm{FDI}, \mathrm{GDP}, \mathrm{EXR}, \mathrm{CO_2}) \tag{1}$$

The model variables are log-transformed for the purpose of an empirical estimate, which reduces the sharpness of the data and improves the distributional features of the variables. Data difficulties related to autocorrelation and heteroscedasticity can be eliminated via natural logarithmic processing except for FI because FI has been taken as a percentage of merchandise imports. Results from log-transformed models are more reliable and effective than results from linear transformation (Benoit 2011).

Mineral resource import (MIS) is the log of total MIS measured in US$ thousands, and main explanatory variable renewable energy capacity (REC) is the log of total energy consumption measured in cumulative in megawatt (MW). REC variable include solar, wind, hydropower, and others. When the literature is reviewed, many studies certainly prefer the data of REC to strengthen the model.

FI is the fuel import and measures percentage of merchandise imports. Fuel imports comprise the mineral fuels, lubricants and related materials.

EI is energy intensity measures kilogram of oil equivalent (koe)/dollars at constant exchange rate, price and purchasing power parities of the year 2015 ($15p). As the CO_2 and other environmental impacts of mineral production are progressively incorporated into the cost structure of mineral not only will the absolute price of mineral increase, but there will also be a relative shift in price between minerals due to the different energy intensities of mineral production processes (Norgate and Haque 2010). Therefore, EI is the major contributor to the emission mitigation. For example, Lin and Ouyang (2014) show that the EI effect makes the greatest contribution to the reduction of CO_2 emissions.

FDI is foreign direct investment and measures balance of payment (BoP) in the current US$. FDI refers to direct investment equity flows in the reporting economy. FDI is the total of equity capital, reinvested earnings, and other capital (Nejati and Bahmani 2020). Although FDI in mineral resources is often a significant long-term investment (Wang et al. 2020), countries with an abundance of natural resources—particularly mineral sources—attract greater FDI. The most significant aspect that defines a country's desirability for international mining investment is its geological potential. Nevertheless, some countries with abundant mineral resources have drawn more FDI than others; for instance, Australia and Canada have drawn more international investment in mining than China and Russia (Vivoda 2011).

GDP is the log of the GDP measured in current US$ as an indicator of economic development. EXR is measure as real effective exchange rate index (2010 = 100) and EXR is calculated by dividing nominal effective exchange rate, which measures a currency's value against a weighted average of many foreign currencies, by a price deflator or cost index (Lenarčič and Ganesh 2020). Islam et al. (2022a, b) reveal that the exchange rate devalued mineral import demands in the long run.

CO_2 is the log of total CO_2 emission from the consumption of fossil-based sources such as oil, natural gas, and coal gas measured in tons CO_2 per capita. The growth of RE needed for the clean energy transition depends significantly on essential mineral resources, which may cause worries

Table 3 CD test statistics results

Variables	CD test	*p*-values
MSI	32.14***	0.000
REC	40.03***	0.000
FI	24.40***	0.000
EI	32.57***	0.000
GDP	36.78***	0.000
FDI	0.09	0.932
EXR	1.02	0.308
CO_2	1.53	0.127

The asterisks ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively

Table 4 The panel CADF unit root test results

Variables	I(0)		I (1)	
	t-statistic	*p*-value	*t*-statistic	*p*-value
MSI	–0.8866	≥ 0.10	–5.3177***	< 0.01
REC	–1.0904	≥ 0.10	–2.2637***	< 0.01
FI	–1.3185	≥ 0.10	–3.7649***	< 0.01
EI	–3.6794***	< 0.01	-	< 0.01
GDP	–0.8465	≥ 0.10	–2.7178***	< 0.01
FDI	–3.2615***	< 0.01	-	< 0.01
EXR	–1.8240	≥ 0.10	–3.1197***	< 0.01
CO_2	–3.1161***	< 0.01	-	< 0.01

The asterisks ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively

Table 5 CS-ARDL results

Variables	Short-term estimates	
	Coefficient	Standard error
ΔREC	1.0766***	0.0436
ΔFI	–0.3097	0.2788
ΔEI	4.1621*	2.3348
ΔGDP	–0.7024	1.0520
ΔFDI	7.1339	9.9379
ΔEXR	1.8196***	0.6560
ΔCO_2	–4.8658*	2.8504
ECM (–1)	–0.2628***	0.0436
Variables	Long-term estimates	
	Coefficient	Standard error
REC	0.8798**	0.3783
FI	–0.2486	0.2042
EI	3.1177**	1.6271
GDP	–0.6739	0.7382
FDI	3.9888	6.8481
EXR	1.4125***	0.5507
CO_2	–3.4936*	1.9319
Observation	280	280
N	14	14

(***, **) denote 1% and 5% significance, respectively

about potential mineral scarcity and associated CO_2 (Wei et al. 2022; Tokimatsu et al. 2018). The worldwide mining and metals sector is responsible for about 8% of the CO_2 emission (Ritchie and Roser 2020).

Although mining has a sizable impact on global CO_2 emissions, this is outweighed by the economic contribution of the sector. Therefore, many studies have recommended for the mineral industry to implement a carbon price (Cox et al. 2022; Zhu and Lin 2022).

Methods

The CD-ARDL model is used in this study to estimate mineral import demand for the 14 countries that were chosen. Thus, the potential joint correlation effects of the strong economic link between the selected countries can be measured. Chudik and Pesaran (2015) claim that the CS-ARDL model enhances the ARDL model with a linear combination of the average cross-sectional of both the dependent and independent variables in order to account for cross-sectional correlation in the error term. Further, the CS-ARDL paradigm regards the 1-year lag of the regressed variable as a weakly exogenous regressor within the error correction process (Sohag et al. 2021). Additionally, the CS-ARDL process makes it possible to significantly control for the unobservable factors that are used to measure the long-term impacts in the regression model. In addition, it makes possible to address cross-sectional dependence (CD) in both the long and short terms (Samargandi et al. 2021; Chudik et al. 2016). Pesaran et al. (2008) recommend the CD test for potential co-correlation effects of strong economic linkages between selected countries. The CD test is suitable for estimating cross-section independence versus cross-section dependence between sample items (Islam et al. 2022a). The mathematical representation of the CD test is as follows.

$$CD = \left(\frac{TN(N-1)}{2}\right)^{1/2} / \hat{P} \tag{2}$$

$\overline{P}$ Represents the levels of pair-wise correlation of the cross-sectional residuals using the augmented Dickey-Fuller (ADF) regression model. *T* is time and *N* is the cross-sectional units. The study may estimate the slope homogeneity across the panel entities after looking at the CD and panel unit root test. Ultimately, the paper assesses the short- and long-term relationships between the variables contained inside the co-integration mechanisms using the cross-sectional autoregressive distributed lag (CS-ARDL) approach. The paper for a number of reasons chose the ARDL model. First, the ARDL model enables simultaneous estimation of the long- and short-term elasticities (Fedoseeva and Zeidan 2018). Second, models with a single I(0), I(1), or mixed order of integration can be handled by the model (Shin et al. 2014). Finally, the ARDL approach also prevents issues with endogeneity (Adewuyi 2016). It is noteworthy that the CS-ARDL paradigm treats the regressed variable's 1-year lag as the weakly exogenous regressors within the error correction framework. Additionally, the unobservable problems that are used to measure the long-term impacts in the regression model are precisely controlled by this technique. Additionally, it makes possible to control cross-sectional dependence (CD) in both long and short runs (Sohag et al. 2021). Equation 3 describes the empirical baseline panel model for dependent variable mineral imports (MSI) using the CS-ARDL method.

$$\begin{aligned}\Delta \mathrm{MSI}_{it} &= \mu_i + \varnothing_i\left(\mathrm{MSI}_{it-1} - \beta_i X_{it-1} - \vartheta_{1i}\overline{\mathrm{MSI}}_{t-1} - \vartheta_{2i}\overline{X}_{t-1}\right)\\ &\quad + \sum\nolimits_{j=1}^{p-1} \pi_{ij}\Delta \mathrm{MSI}_{it-j} + \sum\nolimits_{j=0}^{q-1} \omega_{ij}\Delta X_{it-j} + p_{1i}\Delta\overline{\mathrm{MSI}}_t + p_{2i}\Delta\overline{X}_t + \varepsilon_{it}\end{aligned} \tag{3}$$

ΔMSI_{it} Denotes the dependent variable (mineral sources import); X_{it} means explanatory variables which are REC, FI, EI, FDI, GDP, EXR, and CO_2. While $\overline{MSI}_{t-1}$ denotes the long-run scrutinized coefficient of the dependent variable, $\overline{X}_{t-1}$ shows the long-run scrutinized coefficient of explanatory/independent variables. Furthermore, the short-run coefficient of dependent and explanatory/independent by ΔMSI_{it-j} and ΔX_{it-j}, respectively. The disturbance term is ε_{it}, and $J = 1 \ldots J$ shows the cross-sectional units. Time is

$t = 1 \dots T$, and π_{ij}/ω_{ij} show the short-run coefficient of the dependent and explanatory/independent variables, correspondingly. Lastly, p_{1i} and p_{2i} display the short-run coefficient of the mean of dependent and explanatory/independent variables, respectively.

Empirical findings

The descriptive statistics of the logarithmic variables used in the study models and the correlation matrix of the variables are shown in Tables 7 and 8 in the "Appendix" section, respectively. The aggregate mineral imports' overall mean and standard deviation values are 15.304 and 1.444, respectively, showing improved efficiency and less variability for these metrics among the selected nations for the relevant time periods. According to the correlation matrix, it shows that there is a statistically significant correlation between all of the independent variables and the dependent variable (MSI).

Then, the paper employs the slope homogeneity test. Table 2 presents the slope heterogeneity issue checked by the slope homogeneity test results ($\widetilde{\Delta}\&\widetilde{\Delta}_{adj}$) developed by Pesaran and Yamagata (2008). To further check for homoscedasticity and serial correlation issues, Blomquist and Westerlund (2013) rehabilitated this test ($\Delta_{\mathrm{HAC}}\&\Delta_{\mathrm{HACadj}}$). The findings of the two homogeneity of slope test inquiries are given in Table 2 below.

The results indicate that the p-values are less than 0.01 according to the findings. The null hypothesis of slope homogeneity throughout the panel entities is refuted by this result. The cross-section dependence (CD) test can still be used because different cross-section units have different slopes.

The cross-section independence of the panel units is assessed using the CD test (Hsiao et al. 2012). Additionally, it assists in choosing the right model to use based on the CD's condition (Pesaran 2007). Table 3 displays the results of the CD test statistics and the average correlation (p) values.

As seen in Table 3, CD values are highly significant in the case of MSI, REC, FI, EI, and GDP variables. More importantly, the CD statistics of REC are the highest while FI (fuel import) is the lowest among all other variables.

To check the stationarity of the variables, a panel unit root test called CADF developed by Pesaran (2007) was applied. The CADF test, which dynamically chooses the integration order of each variable separately, is notable for its section unbiasedness (Zhuang et al. 2021). The integration decision order, in particular, is crucial for selecting the best technique for panel data analysis. The order of integration among the variables is mixed according to the CADF estimation (Islam et al. 2022a). However, the use of the CS-ARDL technique for cointegration is supported by the presence of CD and the variable's mixed-order integration state (Li et al. 2020). The panel unit root test results among the variables are given in Table 4.

According to Table 4, while foreign direct investment and CO_2 emission are stationary at the I(0) level, all other six variables are stationary at the I(1) level. Therefore, the CS-ARDL test was employed to discover long-term correlations between variables since the series is stationary at various levels.

The CS-ARDL method links competitively with the co-related effects mean group (CCEMG), the augmented mean group (AMG), and the pooled mean group (Abbasi et al. 2021). The interiority paradox and the heterogeneous slope coefficients can be solved with CS-ARDL (Su et al. 2021). Additionally, it provides reliable outcomes despite issues with cross-section dependence. Even when there are mixed sequential integration/non-stationary difficulties, it can still function well (Zaidi et al. 2021; Tao et al. 2021).

The present paper employs the CS-ARDL method to look at how responsive the overall mineral import demand is to clean energy transitions RE capacity within the fuel import (FI), energy intensity (EI), income (GDP), foreign direct investment (FDI), the exchange rate (EXR), and CO_2 emission in the case of top 14 mineral importing countries. Cross-sectional ARDL is used in this paper to assess both the long- and short-term impacts, as indicated in Table 5.

Table 5 shows the results from CS-ARDL regression. The analysis revealed several explanatory variables that are significant determinants of the clean energy transition. In other words, Table 5 illustrates how sensitive total mineral imports (MIS), one of the key indicators of the transition to clean energy, are to the capacity of RE sources. In the short-term estimation, the error correction coefficient appears to be negative at the level of 1%. This result demonstrates how the variables have a long-term relationship and may be used to modify any short-term shock wave.

The study's most significant finding is that the total mineral imports (MIS) respond favorably to the RE capacity built in the countries with the highest mineral import volumes. Over time, the REC coefficient is significant and positive. This finding demonstrates how the generation of RE raises the import demand for essential minerals in the countries that import the most minerals.

It is widely accepted that large-scale use of RE is one of the most critical steps necessary to reduce global warming (Wang et al. 2021). Thus, it suggests that important minerals are needed for key RE technologies (PV, CSP, Offshore and Onshore wind turbines etc.) to provide RE. This study's finding about RE capacity positively influencing mineral import is consistent with earlier research by Islam et al. (2022a), Calvo and Valero (2022), Ma (2022), and Toro et al. (2020). These authors focused on the mechanical properties of many essential minerals and their ability to generate RE. Furthermore, Chevrel and Ranchin (2018) also support the findings obtained from the analysis that there is a greater need for mineral resources for RE development. A few minerals with expanding markets are aluminum, cobalt, copper, iron ore, lead, lithium, nickel, manganese, silver, steel, titanium, and zinc. In other words, the demand for minerals that are relevant to low-carbon technology is increasing quickly. Hammond and Brady's (2022) emphasis is on the critical minerals used in batteries for RE and electric vehicles.

Table 5 also shows that the coefficient of energy intensity (EI) and exchange rate (EXR) is positive and statistically significant while CO_2 emission is negative and statistically significant in the long run. The long-term positivity and significance of the exchange rate elasticity coefficient (EXR) indicate that the increase in EXR supports the import expansion of vital minerals in the majority of mineral-importing countries. The impact of energy intensity on mineral imports is anticipated because of the large rise in energy demand/intensity brought on by increasing industrialization, urbanization, and globalization (Yasmeen et al. 2022). The literature has also demonstrated the positive impact of expanding energy intensity and the growth of RE (Yu et al. 2022; Nawaz et al. 2021).

Conclusions and policy implications

Metals and minerals are essential for the shift to a low-carbon economy. The demand for the minerals required to create and use green energy technology, such as solar panels, wind turbines, electric vehicles, and energy storage, is increasing as well. In the shift to RE, this rising demand benefits the economies of nations that hold significant quantities of key minerals. In this context, the paper is shown how, for a selected group of 14 countries, the major mineral importing countries' mineral import demand changed in response to the clean energy transitions between 2000 and 2021.

The current paper obtains some noteworthy findings. First, the research supports the study's main hypothesis, which states that REC has a favorable long-term impact on mineral importation (MIS) in the countries that import the most minerals. That is to say, imports of minerals rise as RE sources develop. Secondly, the effects of energy intensity (EI) and exchange rate (EXR) on mineral import are favorable and statistically significant. Finally, CO_2 does not help these countries' demand for mineral imports to grow.

The findings of the paper have some significant policy implications. For instance, it encourages mineral-importing countries to move toward a decarbonized or net-zero emission pathway by utilizing minerals in the generation of RE. However, the recycling of these minerals should be a concern for the decision-makers in these economies. These countries might not succeed in implementing the circular economy goal if these mineral resources are not adequately recycled. Additionally, policymakers should use it to reshape the energy industry to rely more on renewable sources than on non-renewable ones in order to maximize the use of minerals.

In addition to the aforementioned policy recommendations, the rise of RE use is anticipated to boost demand for minerals; hence, policymakers of economies that import minerals should consider this as clean energy output grows. It is inevitable that policymakers in countries, particularly those that import minerals, will establish mineral import regulations to prevent issues with the global transition to clean energy when mineral imports expand. Mainly, the use and development of RE technology are included in the global sustainability paradigm. The most mineral-importing economies are drawn to utilize mineral resources in keeping with the carbon zero target since they are crucial for helping countries transition to clean energy in line with RE ambitions. Hence, the worldwide goal of achieving a decarbonized or net-zero emissions trajectory by the twenty-first century might be implemented by these countries' mineral-driven clean energy generation procedure. Furthermore, the development and maintenance of national power systems depends on vital-critical minerals. In addition, supply chains for these minerals are unstable as the majority of critical mineral resources are concentrated in a small number of countries and geopolitical conditions magnify such risks (Bogdanov et al. 2019). Therefore, given the potential supply–demand imbalance of critical minerals, it is important that governments consider the strategic reserve of such scarce minerals. Finally, given that many current energy projects will eventually be forced to close, it suggests that more secondary sources will be identified in such End-of-Life (EoL) products. So that more essential minerals may be recovered from such EoL products, the policymakers should actively promote recycling activities by boosting the circular economy. A national information system on key minerals, regional EoL product collection sites, and financial subsidies are a few examples of the necessary policies that should be prepared to support recycling initiatives.

The study has a few limitations. First, due to access difficulties, mineral price data, which are important for mineral imports, were excluded from the analysis. However, the research included the exchange rate, which the paper expected to be significant in mineral imports, and it turned out that it had an impact on those imports. Second, the study's analysis of how crucial minerals react to the transition to clean energy is also limited to 14 carefully chosen countries. In light of this, future research will compare crucial minerals and examine their sensitivity to the clean energy transition on a more regional level (OECD, EU, USA, or Middle East).

Appendix

Table 6 Summary of recent empirical literature review of mineral resource

Author/s	Periods	Countries	Variables	Method	Findings
Islam et al. (2023)	1996–2020	China	MI, MIR, GPT, GPA, GPN, GPB	Quantile ARDL approach	It has been determined that the disaggregated measurements of geopolitical risks on mineral imports and increased renewable energy production by mineral imports have a significant impact
Islam et al. (2022a)	1996–2019	9 countries (Australia, Brazil, Canada, Chile, Mexico, Russia, S. Africa, Ukraine, USA)	MI, ISC, IWC, AMP, OP, EXR	CS-ARDL approach	The findings reveal that mineral import demand responds significantly positively to solar and wind power generation
Islam et al. (2022b)	1990–2020	29 OECD Countries	MI, CIM, NIM, ISC, IWC, EGR, COP, NKP, AMP, OP, EXR, GDP	CS-ARDL approach	The findings confirm that overall RE generation supports import demands for minerals over the long term
Luo et al. (2022)	2021–2030	China	10 critical mineral (copper, nickel, manganese, cobalt, zinc, chromium, rare earth, silica, graphite, lithium) reserves and storage	Scenario analysis	The results show that between 2020 and 2050, the increase in clean energy generation and electric vehicle ownership in China will lead to a significant increase in the demand for mineral resources and a shortage in the supply of some mineral resources
Zhu et al. (2022)	2000–2009	China	RED, GDP, RETP, FDI, REC, EI	Quantitatively analyze & dynamic econometric model	As a result, China, as an important critical metals trading country, has a strong trading power and central influence
Nassani et al. (2021)	1990–2019	10 Resource-Abundant Economies	MR, GDP, TO, population, FD, INS	Panel robust least square regression	Trade, financial growth, and energy consumption all contribute to the conservation of mineral resources
Nate et al. (2021)	2050	-	17 mineral and CO_2	Fuzzy logic technique	Scenario 1 demonstrates that cobalt, graphite, and lithium are important battery minerals. While the estimates in Scenario 2 are similar to those in Scenario 1, they are a little more upbeat for iron, aluminum, lithium, graphite, and indium

Table 6 (continued)

Author/s	Periods	Countries	Variables	Method	Findings
Aldakhil et al. (2020)	1995–2018	12 resource-abundant economies	Mineral, GDP, population, R&D, REC, forest area	Panel quantile regression	The findings demonstrate that demand for RE, population density, and forest areas negatively influence mineral resource extraction in varying degrees, while technical cooperation grants and R&D expenditures are both positive and significant predictors of mineral resource extraction
Beylot et al. (2019)	2050	France	Minerals (steel, aluminum, copper, and concrete productions), CO_2, electricity generation	Forecasting	Results are given as upper and lower bounds on the likelihood that the number of materials needed and the ensuing climate change effects of producing those materials should be less than a given value
Ouedraogo (2016)	1970–2012	USA	MR, GDP, population, employment, manufacturing/construction/service earnings	Spatial durbin model	The findings indicate that in counties relying on natural resource extraction, employment growth in the mining sector was more rapid during boom times and slower during busts

MI mineral imports, *CIM* copper imports, *NIM* nickel imports, *ISC* installed solar capacity, *IWC* installed wind capacity, *EGR* renewable electricity capacity, *COP* copper prices, *AMP* average mineral prices, *OP* oil prices, *EXR* exchange rate, *GDP* gross domestic product, *RED* renewable energy power generation capacity, *RETP* renewable energy technology progress, *REC* renewable energy consumption, *EI* energy intensity, *MR* mineral resources, *TO* trade openness, *FD* financial development, *INS* insurance and financial services, *MIR* mineral import-augmented renewable energy generation, *GPT* geopolitical risk threat measure, *GPA* geopolitical risk act measure, *GPN* geopolitical risk narrow measure, *GPB* geopolitical risks broad measure

Table 7 Descriptive analysis results

Variable	Mean	Standard deviation	Minimum	Maximum	Observations
LMSI	15.1304	1.4446	10.2641	19.0838	308
LREC	10.17230	1.5262	6.6682	13.8355	308
LGDPPC	9.7832	1.2055	6.0943	11.1460	308
LFI	2.4597	0.7929	–0.7906	3.6767	308
LER	4.5649	0.1676	3.9118	5.0304	308
LEI	–2.0992	0.4666	–2.9374	1.1448	308
LCO$_2$	2.0905	0.6642	–0.1199	3.0189	308
FDI	0.0007	0.0299	–0.1619	0.2018	308

Table 8 Correlation matrix

	LMSI	LREC	LGDPPC	LFI	LER	LEI	LCO$_2$	FDI
LMSI	1							
LREC	0.5067***	1						
LGDPPC	0.1589***	–0.0279	1					
LFI	0.2589***	–0.1641***	–0.0632	1				
LER	0.3867***	–0.0167	0.2776***	0.2353***	1			
LEI	–0.0774	0.0117	–0.3266***	–0.2060***	–0.0668	1		
LCO$_2$	–0.0041	–0.0586	0.7598***	–0.3116***	0.1064*	0.2322***	1	
FDI	0.1587***	–0.1092*	0.2958***	0.0282	0.0852	–0.0949*	0.1694***	1

***, **, and * show significance at 1%, 5%, and 10% level respectively

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