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Interlinkages Between Financial Markets and Minerals (1990–2023): Implications for Global Energy Transitions and Environmental Sustainability

Hamza Akram[1] | Jinchao Li[2] | Muhammad Ashar Asdullah[3] | Muhammad Salman Shabbir[3] | Waqas Ahmad Watto[4] | Tuba Rasheed[5]

[1]School of Economics and Management, North China Electric Power University, Beijing, China | [2]Beijing Key Laboratory of New Energy and Low-Carbon Development, North China Electric Power University, Beijing, China | [3]York St John University, London, UK | [4]Department of Accounting, The Superior University Lahore, Lahore, Pakistan | [5]Department of Economics, The Superior University Lahore, Lahore, Pakistan

Correspondence: Muhammad Salman Shabbir (m.shabbir@yorksj.ac.uk)

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ABSTRACT

This paper examines the nexus between financial markets (FM), mineral resources, and global energy transitions (ET) between 1990 and 2023 in the 20 leading countries exporting mineral resources, focusing on their impact on environmental sustainability. Cross-sectional ARDL, augmented mean group (AMG), and common correlated effects mean group (CCEMG) estimators are used for cross-sectional analysis of developed and developing countries. The findings suggest that mineral markets (MM) play a pivotal role in guaranteeing sustainable energy shifts, and FM negatively impacts the situation in the short and long term. Renewable energy consumption (REC), external investment, and digital governance (DGI) are developed countries' primary strategies for achieving COP-26 sustainability objectives. The findings indicate that the Digital Governance Index (DGI) and FDI have varied impacts on energy transition in the economies. Developed countries enjoy the opportunities of improved and modernised digital systems and green FDI. In contrast, developing countries must strengthen e-governance and encourage sustainable investments to support SDGs 7, 9, and 13.

1 | Introduction

Sustainable energy sources' financial, environmental, and technological feasibility is beneficial compared to conventional fossil fuels (Gayen et al. 2024). Renewable energy sources have been vital in carbon neutrality (Saeed and Siraj 2024). Since these sources are concerned with energy efficiency, REC can decrease carbon CO_2 emissions by 32% and 37%. This emphasises the significance of the shift to a low-carbon energy system to achieve the objectives mentioned in the Paris Agreement (Boretti and Pollet 2024). ESCAP (2023) also states that additional focus is put on cutting energy intensity, which is made possible by a strategic ET and efficiency improvement, which has played an essential role in improving environmental performance. Then, in previous studies, several digital and non-digital factors were studied to comprehend their impact on adopting REC (Jarvie-Eggart et al. 2024)—technological innovations, digital development, and CO_2 emissions (Eweade et al. 2024). Policymakers should aim at clean energy initiatives that are in line with the goals of sustainable development.

Wang et al. (2023) also state that active promotion of REC is prevalent in the developed countries that have signed such agreements as the Kyoto Protocol. The shift to REC has several benefits for countries, including reducing fuel reliance and enhancing digital stability (Lévy and Robinson 2017). One of the main goals of economies is to balance digital development with environmental sustainability. Many countries

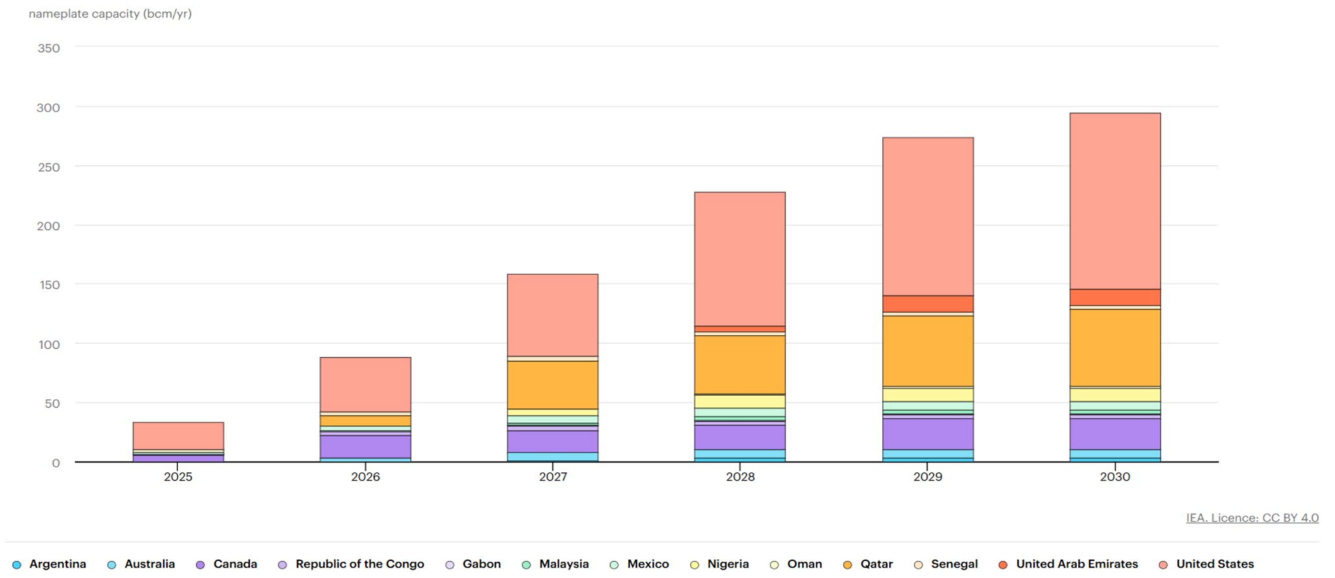

FIGURE 1 | Projected global energy transition (2025–2030).

have geographical characteristics that precondition their being highly favourable in harnessing the resources of the REC, such as hydroelectric, solar, and wind energy (Hassan et al. 2024). Nevertheless, a study by Unnasch (2022) shows that some Asian economies have not fully utilised this potential despite their huge global potential in the energy sector. According to Ekeke and Uprasen (2020), the energy sector is necessary for climate-related pollution. Empirical data on energy have frequently been studied to determine the effectiveness of the energy indicators and policies in curbing CO_2 emissions.

Sustainable Development Goals (SDGs) 7, 9, and 13 all support access to clean energy, strong infrastructure, and action on climate as the main pillars of sustainable development. This study, in the form of empirical evidence, shows that digital governance (DGI) and foreign direct investment (FDI) use differentiated influence on economies. Advanced digital systems that promote renewable integration and outward green FDI in favour of low-carbon innovation are enjoyed by developed countries. Contrarily, the developing world must focus on enhancing e-governance, regulatory transparency, and sustainable FDI to fund renewable energy and technology development. The consistency of these results with SDGs 7, 9, and 13 suggests the significance of digital transformation, sustainable finance, and clean energy investment to have an inclusive and climate-resilient energy transition globally.

However, most of these studies are highly focused and limited to a single section of the empirical data or regulatory frameworks. The comparative analysis of empirical data and energy policies has not received much international attention, and the strictness of energy regulations is frequently disregarded. As Ayele (2022) points out, contemporary academic literature pays more attention to energy efficiency and transition as a crucial tool in climate change mitigation. Financial development has three primary channels in which the theory of the energy trade influences the adoption of the REC: the size of the financial sector, the nature of financial instruments offered, and technological development. With the development of economic systems, uniting these aspects has become more complicated.

Figure 1 draws the approximate export terminal LNG capacity in millions of tonnes per year estimated in the globe between 2025 and 2030 using the statistics of the International Energy Agency (IEA 2025) and the US Energy Information Administration (EIA 2025). This figure depicts that the global LNG capacity has grown significantly, with the United States and Qatar leading the growth, as Nigeria comes next, with Australia, Canada, and Argentina recording relatively decent growth. This distribution points to lopsided but worldwide development of LNG between established and emerging producers.

LNG capacity is introduced as an element of the energy transition paradigm due to popular belief that natural gas can serve as a so-called bridge fuel that facilitates the transition of high-carbon fossil fuels (i.e., coal and oil) to less polluting and more versatile energy sources. Despite LNG being a fossil resource, it has a lower carbon intensity. It contributes to stabilising renewable power systems and, hence, LNG remains a transitional element to near-term decarbonization agendas and power security during the transition.

The mining sector is distinguished by the large consumption of resources and the level of impact on digital success. According to Siklos (2022), it is forecasted that metals and other minerals like vanadium, indium, cobalt, nickel, graphite, and lithium will undergo exponential production growth by 2050. These are astonishing growth rates estimated to be 585, 241, 964, 173, 108, and 383, respectively, due to the increasing demand for greener energy solutions. These minerals and metals are essential elements in transmitting and storing clean energy. Thus, countries with unfilled natural resources in the form of minerals are now on the verge of becoming the leading suppliers of these essential resources essential to the energy processes in the field of sustainability (Lei 2021).

Considering such findings, Hodgkinson and Smith (2021) state that it is necessary to seek innovative, green, and safe mining technologies, which can support mitigating climate change. In the same vein, Wang et al. (2023) emphasise the fact that sustainable mining processes are the key to a green-industrial activity and the spread of more environmentally friendly energy. The development of the financial market is very influential in the extent of consumption of REC, regardless of the predetermined connection between the growth of the digital world and the consumption of REC (Hodgkinson and Smith 2021; Siklos 2022). The process of evolution as it relates to financial systems has the potential to leave an imprint on energy usage, as it could restrict the development of digital systems (Bueno et al. 2024). For example, when FM provides energy-related financial products like consumer loans to finance energy projects, the direct relationship between energy consumption and financial market maturity is obvious. The thriving of FM reduces consumer risks, which is essential in creating a successful, digital, sustainable environment and wealth creation.

Several researchers have emphasised the importance of the growth of FM to ensure sustainable business practises (Ayadi and Ronco 2023; Eweade et al. 2024; Mahugu 2022). Based on this insight, such a study aims to unpack these complex relationships between financial and MM and their role by ET in the top 20 mineral-exporting countries. Based on these perspectives, this study is envisioned to have a fourfold objective of contributing to the available literature on the effect of financial and MM on ET, particularly using countries with a high mineral export. The study is unique in that it has explored the subject through the prism of energy trade instead of focusing solely on clean energy consumption. We use statistical methods such as cross-sectional autoregressive distributed lags (CS-ARDL) to capture short-term and long-term dynamic effects. To justify findings, AMG and CCEMG procedures have considered the possibility of such pitfalls as endogeneity and cross-sectional dependence. The analysis is not restricted to the monolithic analysis; the researchers divide the countries that export minerals into the developed and developing categories based on the income level.

The given partition enables making a subtle comparison between the developing and developed economies in 30 years (1990–2023) and the roles of the financial and mineral markets in the energy transition process, which are different at various levels of development. It is based on the analytical framework where the critical control variables (including the intensity of carbon emission (CEI), the use of renewable power (REC), digital governance (DGI), and foreign direct investment (FDI)) are incorporated to enhance the robustness of the framework and the inclusion of the multidimensional variables of sustainability. Empirical evidence shows that DGI and FDI have quantile-specific effects. On the one hand, digital governance can be more influential on the economies of developed countries as it has some consequences related to technological innovation. Conversely, the contribution of the FDI to the developing world in renewable infrastructure and clean energy investments is larger. These effects further distinguish themselves, and that is why SDG 7 (Clean Energy), SDG 9 (Innovation and Infrastructure), and SDG 13 (Climate Action) are considered in the study and hence offer policy implications based on empirical data. The remainder of the research was designed in the following way: Section 2 covers the relevant scholarly works in detail. The following section, Section 3, explains the research methods and dataset. Section 4 then offers a data-driven exploration of the interplay between financial and MM and their role in ET within mineral-dependent economies. Conclusions and interpretations are provided in Section 5, where the study draws to a close.

2 | Literature Review

More research is needed into the connection between MM and ET. In contrast, much research is on how fossil fuel use and energy consumption shape digital dynamics. On the other hand, scholars are becoming increasingly interested in the interplay between financial indicators, MM, and their potential effects on REC adoption. Cleaner energy is critical to lowering energy production's volume and security risks, hence stimulating digital growth, as per the researchers Pan (2016) and Naudé and Nagler (2022). Climate change, energy transition, and renewable energy investments influence energy security risks in major energy-consuming countries, revealing that renewable transition strengthens energy security whilst climate change, trade openness, and financial development increase vulnerability (Bashir et al. 2025). Nonetheless, significant increases in greenhouse gas emissions and rising fossil fuel prices can increase demand for green energy, increasing worldwide reliance on renewables (Wang and Wang 2022). As a result, increasing research bodies are dedicated to exploring interconnections amongst energy use, digital development, financial inclusion, trade liberalisation, varied exports, and environmental metrics across different nations and regions (Esram and Hu 2021; Hodgkinson and Smith 2021; Mahugu 2022).

Environmentally friendly energy systems have integrated sustainable energy resources in worldwide initiatives to address climate change and shift towards using environmentally friendly energy resources. The study area has various energy sources such as solar, wind, hydropower, and bioenergy. Specifically, photovoltaic technology has taken a significant step in solar energy and is a prominent participant in the sustainable energy industry (Liu et al. 2016). Similarly, wind energy has increased significantly, due to the increasing size of the turbines and their improved efficiency (Lévy and Robinson 2017). These inventions show that it is necessary to be aware of the possibility and variety of sustainable energy sources. The invention of technologies has greatly facilitated the use of sustainable energy. The article demonstrates that in 25 countries of the EU, FinTech directly and indirectly positively influences the green energy transition and ecological footprint, which means that FinTech promotes green energy and reduces environmental footprint through energy transition (Ahmad et al. 2024). Technological innovation, strict environmental regulations, and political globalisation that can contribute to the achievement of net-zero emissions are promoting the uptake of renewable energy and the reduction of the use of fossil fuels in OECD countries (Rehman et al. 2023). The research conducted by Jongen (2018) suggests that to integrate intermittent renewable energy sources, e.g., solar and wind power, into the energy grid, an energy storage technique, e.g., a battery, is necessary. Also, grid management systems and energy efficiency have been enhanced, enhancing the sustainability of energy sources.

The major component of sustainable energy adoption is policies and regulations. Recent research shows that tax incentives, renewable portfolio standards, and feed-in tariffs are critical to the process of investments in sustainable energy projects (Mahugu 2022; Siklos 2022; Wang and Wang 2022; Wang et al. 2023). Such policies establish a favourable energy development environment to favour the transition towards cleaner energy sources. Besides the technological and policy impacts, sustainable energy resources' environmental and online effects are immense. They also have a high level of environmental benefits, especially in reducing the levels of greenhouse gases and addressing air pollution, which are reflected in the study (Ayele 2022; Dai et al. 2023). The alternative clean energy sources have the potential to cut down coal reliance in South Africa, and it was discovered that renewable and hydro energy restrict coal greatly, even as economic growth and population density scale it up (Erdogan et al. 2025). Moreover, long-term energy investments have proven to spur digital development, and research has presented job creation and digital contributions (Gielen and Lyons 2022).

Energy and climate policy uncertainties affect renewable energy–related mineral production in China, finding that climate policy uncertainty boosts mineral output. In contrast, energy policy uncertainty hinders it, highlighting the need for stable policies to sustain the clean energy transition (Pata and Pata 2025). Ngo et al. (2022) investigated how REC affects CO_2 emissions in Sub-Saharan Africa along with the BRICS economies. As per this research, the influence of REC on greenhouse gas emissions throughout 245 countries is divided into income groups. According to their study, renewables typically reduce CO_2, but Leicht and Fitzgerald (2022) and Zafar (2021) observed that an exception arises in lower-middle-income economies. Academic discourse focuses primarily on digital measures of local and global significance and the delicate relationship involving energy policies, which utilised the Analytic Hierarchy approach to generate the ET trajectory in 14 nations. Conversely, researchers introduced a specialised index to measure ET within the global energy matrix (Pan 2016). Esram and Hu (2021) also analyzed the associations across REC, GHG emissions, and regulatory excellence in 32 Asian nations from 1996 to 2014. Through the MMQR (moments' quantile regression) method, they discover which regulatory prowess, combined with more fruitful energy sources, correlates with serious environmental effects.

The results of the studies by Zou et al. (2024) prove the significance of ET in promoting the attainment of a low-carbon social structure. Mineral resources such as rare earth elements, lithium, cobalt, and so forth are the key components of the REC technologies, such as wind turbines, energy storage systems, or solar panels.

The sources are the foundation to manufacture photovoltaic cells, wind turbine magnets, and high-capacity batteries. The world has moved to sustainable energy sources; thus, the demand for these minerals has considerably risen in recent years (Siklos 2022). The sustainability of the mining extraction practises is one of the areas of concern. Mining and processing these minerals may negatively affect the environment and society. Ensuring responsible mining and ethical supply chains is essential to match mining resource exploitation with the clean energy sustainability objectives (Ekeke and Uprasen 2020). Besides this, there is the geopolitics of mineral resources. Such resources occur in specific locations that question resource accessibility, dependence on trade, and potential conflicts (ESCAP 2023). The role played by mineral resources is to enhance the capability and efficiency of renewable technologies regarding sustainable energy sources. For example, it is impossible to manufacture permanent magnets on wind turbines without utilising rare earth elements, making them more effective (de Prado 2023).

Recycling is being explored, and innovative material technologies are being explored to bridge the gap between mineral resources and sustainable energy requirements. Recycling can be done to reduce the burden on lithium and cobalt resources, including lithium-ion batteries (Unnasch 2022). Balancing the increasing need for such resources and environmental and ethical factors, and ensuring clean ET sustainability, is difficult. Solving these challenges will be the key to a sustainable and green energy future. Equally, the International Energy Agency also attests that augmenting energy efficiency has been an exceptionally influential technique of demand management, which is critical in climate change mitigation. Using an empirical approach based on Australia's energy consumption trends, the author supports the significance of energy efficiency in mitigating greenhouse gas emissions (Luca 2023). The scholarly consensus is that increasing energy efficiency is a wise approach that benefits the protection of the environment and the creation of sustainable digital models.

The study by Schoch et al. (2012) involved the dynamic and Granger causality techniques to investigate the relationships amongst financial stability, environmental health, and energy consumption in South Asia between 1980 and 2012. They also concluded that energy consumption reduces ecological quality, and economic stability is a positive factor. The research by Wang et al. (2023) assumed that CO_2 production in different industries could be decreased by means of an increase in the efficiency of energy use. Increasing the direct relation between CO_2 and energy consumption, energy efficiency promotes the use of friendly energy sources and is also very important in mitigating greenhouse gas emissions. In their study, Gelb et al. (2021) observed that such gains in energy efficiency would help reduce CO_2 emissions in the cement industry by large margins. Conversely, Zafar (2021) aimed at breaking down the possible impact of the energy transformation in the paper and pulp industry in Sweden on digital development and CO_2 emissions, yet their analysis was directed at the change of efficiency, as well as electrification, which were determined as the key drivers of the CO_2 decrease. Stress the growing popularity of the eco-friendly agenda and the possibility of lucrative profits as the motivators of the given trend (Jongen 2018; Liu et al. 2016).

To make this type of investment, financial instruments such as green bonds and impact investing have become a notable place. Green bonds have become a possible tool to channel funds into sustainable energy projects, as Liu et al. (2016) have emphasised, and these align with investors' sustainability goals. In FM and policy discussions, risk and return analysis of sustainable energy investments is critical to evaluate. They discussed the risk factors of REC investments and diversification possibilities (Lévy and Robinson 2017; Mahugu 2022). According to Jongen (2018), these risk–return profiles inform the decisions made by investors, and the profiles can assist investors in realising sustainable finance strategies.

Moreover, the literature highlights the significance of open and facilitating policy and regulatory regimes in REC investment (Gelb et al. 2021; Ngo et al. 2022; Zou et al. 2024). Regulatory uncertainty may, however, deter investment. Also, conducive and stable environments must exist, as evidenced by regulatory uncertainty. The dynamic in the fast-changing world of sustainable energy requires technological developments to transform the dynamics of FM.

New investment opportunities and challenges exist due to the latest innovations, such as decentralised energy generation, energy storage solutions, and smart grids. According to Laustsen, FM should adapt to such innovations to remain ET. The necessity to facilitate the transition and energy efficiency policy makes it one of the keys to developing a low-carbon digital environment (Ngo et al. 2022; Zafar 2021). According to the examination of scenarios, to mitigate CO_2 emissions, drawn curves were created to formulate particular energy policies (Alwerfalli 2022; Dai et al. 2023). Politically, Andrews-Speed (2016) suggested that the traditionalist society may become an obstacle to the proliferation of low-carbon energy policies. The array of focal points and methodologies to analyse it is to leave a mash-up, but a trembling conclusion is shown in the academic canvas (Salim 2022). It is highly committed to energising ET and enhancing clean energy initiatives as the planks of climate amelioration measures.

The study of the mining situation highlighted the necessity of proper risk evaluation throughout all fossil fuel-oriented mining (Gielen and Lyons 2022; Jongen 2018). In the same way, Unnasch (2022) pointed out that the increasing concerns connected with the availability and importance of metals are promoted by increased consumer demand. Mining projects should prove their risk management, evaluation, and mitigation skills. Any lapses would further debilitate the transition to a low-carbon era in the critical metals needed by the ET. Expanding on the business field, Liu et al. (2016) suggested that prudent regulatory frameworks can protect against the adverse consequences of excessive dependence on natural resources and steer the discussion towards financial growth. Sound business guidelines may eliminate the curse of economic resources and reduce the effect of oil price changes on the stock returns of specific industries (Ekeke and Uprasen 2020; Ojeka et al. 2023). The multifaceted relationship between digital development and ecological quality was investigated in various countries or regions (Esram and Hu 2021; Gielen and Lyons 2022; Memarpour et al. 2023), which proves that financial inclusion is positively related to ecological footprint; the relationship changes with quantiles. Whereas REC hurts environmental quality, digital expansion enhances it.

The techniques that de Prado (2023) used include FM-OLS, D-OLS, MMQR, and FE-OLS, amongst others, to explore how financial inclusion leads to European environmental pollution. They also found a positive relationship between digital expansion and environmental pollution. However, the Dynamic ARDL approach helps REC overcome this effect as the analysis of long-term and short-term relationships between sustainable digital parameters and the environment's health is conducted in reference to China (Hanaček and Martinez-Alier 2022). The results highlighted that sustainable finance and ecological footprint support ecosystem conservation, and the sustainable digital elements are of utmost importance in the degradation of the environment within both periods. To determine the correlation between the growth of DGI and energy consumption, Chudik and Pesaran (2015) employed the use of Granger causality and the Johansen Cointegration method. Their results showed a strong positive correlation between FM and long-term digital development.

Moreover, Saud et al. (2023) noted that the energy demand is proportional to the flourishing of FM. Lévy and Robinson (2017) reiterated this feeling, postulating that a stronger financial market environment will cause an increased appetite to invest and take energy. Many influencing factors, such as business, direct effects, and wealth, significantly impact the energy trajectories. The wealth effect, which is driven by FM and built up by established connections, becomes the driving force, according to Pillay et al. (2023). This impact is enhanced when the use of digital activity reaches its peak and new businesses are created, which raises the amount of energy demand in the world. Many research works have tried to unravel the relationships all over the energy consumption as well as financial market dynamics and have found a hodgepodge of results (Alwerfalli 2022; de Prado 2023; Ha et al. 2023; Ngo et al. 2022; Zou et al. 2024). Empirically, the GMM was used to determine the positive correlation between energy consumption and financial market development in 27 European countries (Ayele 2022; Peng et al. 2023). Equally, a positive relation was found between the growth of FM and energy consumption in a VECM.

Notably, it also emphasised the importance of the development of FM when it comes to the popularisation of the consumption of the REC, especially when foreign investments introduce more environmentally friendly forms of energy (Ojeka et al. 2023; Raskin 2016; Unnasch 2022). Although the impact of digital expansion on sustainable energy is being listed, the energy-economy nexus still has unexplored spaces that can be discovered. This discovery is consistent with the priorities of world sustainability since it empirically validates SDG 7 (Clean Energy), SDG 9 (Innovation & Infrastructure), and SDG 13 (Climate Action). The results indicate that digital governance (DGI) can maximise energy transition efficiency in developed economies through innovation and regulatory transparency, foreign direct investment (FDI) by developing economies, and funding renewable infrastructure and technology transfer. The energy changes are determined by numerous dynamics, including REC and urban sprawl, foreign investments, and CO_2 emission intensity, and each comprises its tale in both temporary and long-term lines. In G7 countries, the process of sustainable development occurs due to energy storage and clean fuel innovation, which are not only accomplished through the spending of R&D but also because of compliance with the technological growth and innovation necessary to incorporate SDG 7 of sustainable development (Pata and Pata 2025). These remarkable impacts can provide practical information to policymakers to introduce a balance between the environment and economic goals by emphasising that individual solutions can ensure a lasting change in the energy conversion of mineral exporters.

The conceptual framework in Figure 2 brings together Finance (FM), Minerals (MM), and Energy Transition (ET) into a single model, which explains the interdependence of the activities of these models to realise sustainable and low-carbon development. It shows how the two financial processes and the accessibility of mineral resources in the energy transition process interact, and how policy and governance are moderating forces that establish sustainability and equilibrium between the two. This model is initiated by Finance (FM) and provides the capital and incentives required to invest in renewable energy technologies through green bonds, sustainable financing, and impact investing (Liu et al. 2016; Mahugu 2022). The bottom is minerals (MM): they are the basic raw materials, such as lithium, cobalt, or rare earth, that are used in the production of solar panels, wind turbines, and energy storage systems (de Prado 2023; Siklos 2022). Energy Transition (ET) is directly captured by FM–MM interaction as the transformative product, the better utilisation of renewable energy, reduced emissions of greenhouse gases, and increased environmental sustainability.

3 | Methodology

3.1 | Theoretical Frameworks

This research paper has been founded on energy trade and digital sustainability theory. The energy transition (ET) conceptual framework is the dynamic outcome of institutional change, resource flows, and institutional change. The energy trade theory is based on the idea that nations with abundant valuable resources of minerals turn to extractive exports to finance the development of industry and energy, and, through this process, their trajectory towards switching to renewable sources (Rao et al. 2024). To capture the importance of resource dependence and international capital flows on national energy formations, the mineral market (MM) and foreign direct investment (FDI) are included (Gold and Tregenna 2024; Rao et al. 2024).

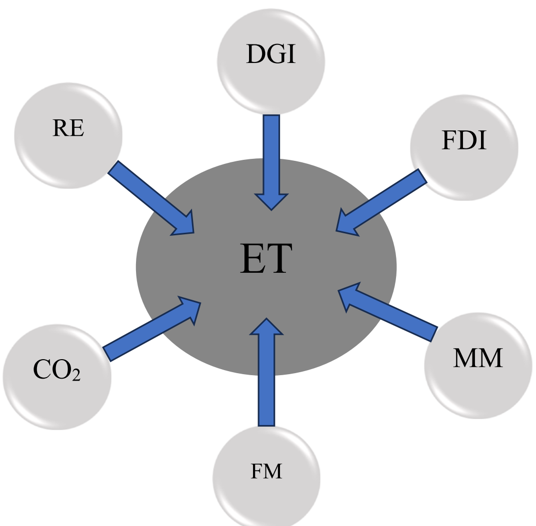

FIGURE 2 | Conceptual framework.

Simultaneously, the digital sustainability theory states that digital governance and financial technologies contribute to improving energy efficiency, environmental monitoring, and green innovation (Zhang et al. 2025). Therefore, introducing the Digital Government Index (DGI) and financial markets (FM) factors reflects the contribution of digital and financial infrastructure to sustainable transitions. Besides, carbon emission intensity (CEI) and renewable energy consumption (REC) are environmental performance indicators, where economic and technological development are connected to ecological achievement (Wang and Zhang 2024).

The study to empirically test these theoretical linkages utilises the CS-ARDL model to study both the dynamic short-run and long-run interdependencies, per the energy trade theory concerned with dynamic adjustment processes. Also, the AMG and CCEMG estimators ensure that they resist cross-sectional dependence because energy and digital shocks in one economy may spill over to other economies. This theoretical-empirical convergence ensures that the model measures relationships and operationalises the conceptual interrelationship between trade, finance, digitalization, and sustainability.

3.2 | Data

This paper analyses the mutual dependence between ET, MM, REC, DGI, FDI, FM, and CEI of the 20 largest mineral-exporting countries between 1990 and 2023. The International Monetary Fund (IMF) provides financial market measures to gauge the breadth, accessibility, and efficiency of these measures. The data on REC, FDI, and CEI have also been obtained using the World Development Indicators, and data on DGI have been obtained using the European Data Portal, as shown in Table 1. The variables are transformed into a logarithmic scale to increase the data integrity and minimise the influence of extreme values.

The dependent variable of the study, the Energy Transition (ET), is the proportion of renewable energy to total final energy consumption (%) according to the World Development Indicators (1990–2023), and it is log-transformed to achieve normality. The Mineral Markets (MM) variable, the value of the major minerals (lithium, copper, nickel, cobalt, iron) export was obtained with Trading Economics and confirmed with UNCTADstat, which was also log-transformed to lessen dispersion. The Digital Government Index (DGI) was retrieved from the European Data Portal, and the gaps were sealed with the help of linear interpolations to ensure consistency and strength in the dataset.

The research used 20 large countries that were major mineral exporters (1990–2023) according to WDI (i); (ii) data availability of the significant variables (FM, MM, ET, REC, FDI, DGI, CEI); and (iii) regional and economic diversity. The World Bank (2023) category of developed and developing countries was based on using indicators of GDP per capita and industrial structure. Developed economies: Australia, Canada, the United States, Norway, Russia, Japan, France, Germany, the United Kingdom and South Korea. Emerging markets: Chile, Indonesia, Peru, South Africa, China, India, Brazil, Mexico, Saudi Arabia, Nigeria. The classification allows the comparative analysis of the impact of financial and mineral markets on the energy transitions at various stages of development.

TABLE 1 | Study variables description.

Variable	Definition/Measurement	Source
Energy Transition (ET)	Share of renewable energy in total final energy consumption (%)	World Development Indicators (WDI, World Bank)
Mineral Markets (MM)	Aggregate export value of metallic and non-metallic minerals (USD millions)	Trading Economics (TE), verified with UNCTADstat
Digital Government Index (DGI)	Composite index measuring the extent of digital governance and ICT adoption.	European Data Portal (EDP)
Financial Markets (FM)	Index measuring financial market depth, accessibility, and efficiency	International Monetary Fund (IMF)
Foreign Direct Investment (FDI)	Net inflows of foreign investment as a percentage of GDP	World Development Indicators (WDI, World Bank)
Carbon Emission Intensity (CEI)	CO_2 emissions per unit of GDP (kg per 2015 USD)	World Development Indicators (WDI, World Bank)
Renewable Energy Consumption (REC)	Proportion of renewable energy in total energy use (%)	World Development Indicators (WDI, World Bank)

Abbreviations: EDP, European data portal; IMF, International Monetary Fund; TE, trading digitals; WDI, World Development Indicators.

This study divides the sample into two significant categories: developing economies, represented by Model 1, and developed economies, designated by Model 2. Model 3 consolidates the complete group of 20 countries that export minerals. The authors use the CS-ARDL technique, which Chudik and Pesaran (2015) proposed to decode immediate and long-term associations. As highlighted by Khan et al. (2020), to increase the reliability of the results derived from the CS-ARDL method, the study also employs panel estimation techniques, AMG and CCEMG, as described by Pesaran (2007). The Equation below can be used to illustrate the research model:

$$ET_{xt} = \varphi_O + \varphi_1 MM_{xt} + \varphi_2 FM_{xt} + \varphi_3 REC_{xt} + \varphi_4 DGI_{xt} + \varphi_5 FDI_{xt} + \varphi_6 CEI_{xt} + \varepsilon_{xt} \tag{1}$$

In this Equation, (φ_O) represents the intercept. The coefficients of the independent variables range from φ_1 to φ_6. (xt) stands for the error terms. 'x' and 't' are indices representing, respectively, the cross-sections (the 20 mineral-exporting economies) along with the time frames (from 1990 to 2023). These countries have been separated into six distinct categories. Intense hues correspond to greater values of the variables, whereas light hues represent lower values. Over the past four decades, these mineral-exporting nations have undergone significant changes. The influence of MM varies significantly between developing and developed economies.

3.3 | Econometric Estimate Approach

3.3.1 | Evaluation of SH and CSD Coefficients

In our study, the coefficients of CSD and SH are identified, which is not typical of traditional approaches, which often overlook these tests, contradicting the ability to obtain reliable results (Gelb et al. 2021; Ulucak and Khan 2020). Baltagi and Hashem Pesaran (2007) state that the SH test is sufficiently robust to satisfy the assumptions associated with coefficient homogeneity.

Below are the representatives of SH formulas:

$$\Delta SH = \sqrt{Z} \times \frac{1}{\sqrt{2h}} + UZ^{-1} - h \tag{2}$$

$$\Delta_{ASH} = (Z)^{(1/2)} * \left[(2h(S-h-1)/(S+1))^{(-1/2)}\right] + \left[(1/Z)U - 2h\right] \tag{3}$$

Equation (2) calculates the variable ΔSH is determined by the combination of the square root of Z scaled by the inverse square root of twice h, the product of U and the inverse of Z, and the subtraction of h. and the subtraction of Equation (3) calculates Δ_{ASH} using a similar structure but with a complex fraction within the square root term, involving 2h, S, and U, and subtracting 2h from the result. Both equations express relationships amongst these variables to determine ΔSH and Δ_{ASH}, respectively.

3.3.2 | Testing for Unit Root

Researchers utilise unit root tests of the second generation rather than first-generation LLC (Levin et al. 2002). In particular, we employ ADF (which is cross-sectional) by Pesaran (2003) alongside the IPS (which is cross-sectional) by Pesaran (2007). The most recent iteration's tests resist CSD and slope coefficient inconsistency. Equation (4) is employed to depict the unit root test.

The Cross-Sectional Dependence (CSD) test evaluates whether residuals across cross-sections are correlated. The null hypothesis (H_0) states that there is no cross-sectional dependence amongst the units, whilst the alternative hypothesis (H_1) indicates the presence of cross-sectional dependence. Rejection of H_0 confirms that the panel series is interlinked across countries, justifying the use of second-generation estimators.

Equation (4) presents the CADF specification:

$$\Delta N_{xt} = \rho_x + \rho_x N_{xt-1} + \rho_x \cdot \Delta A_{t-1} + \sum_{h=0}^{v} \left(\rho_{xh} \cdot \Delta N_{t-1+h}\right) = \frac{1}{v} \sum \left(\rho_{xh} \cdot \Delta N_{(xt-1)-h}\right) + \varepsilon_{xt} \tag{4}$$

The Equation ΔN_{xt} models the change in a variable N at time 't'. It depends on several factors, including a constant ρ_x, the previous N value at time '$t-1$', the change in a variable ΔA at time '$t-1$', and a weighted sum of terms involving $\rho_{xh} \cdot \Delta N_{t-1}$, and h for values of h from 0 to v. The Equation also incorporates an error term ε_{xt}, representing random noise in the model. Consequently, the CIPS unit root test metric can be expressed as Equation (5).

$$CIPS = \frac{1}{Z} \sum_{x=1}^{v} CADF_x \tag{5}$$

In Equation (5), CIPS calculates a particular value, and it is obtained by summing a series of $CADF_x$ values for x ranging from 1 to v. Each $CADF_x$ value is weighted by the reciprocal of Z. In essence, it represents the aggregation of $CADF_x$ contributions across a range of x values, adjusted by the factor of $\frac{1}{Z}$.

3.3.3 | Westerlund Test

The cointegrated connection amongst indicators like FM, MM, FDI, REC, ET, CEI, and DGI intensity has been examined using an error correction (EC) approach, according to Westerlund (2007). The overall framework for this evaluation is outlined below:

$$\mathrm{P_t} = \frac{\rho}{\mathrm{SE}(\rho)} \tag{6}$$

$$\mathrm{P_a} = \mathrm{t}(\rho) \tag{7}$$

$$\mathrm{G_t} = \frac{1}{\mathrm{Z}} \sum_{\mathrm{x}=1}^{\mathrm{z}} \left(\frac{\rho_{\mathrm{x}}}{\mathrm{SE}\left(\rho_{\mathrm{x}}\right)}\right) \tag{8}$$

$$\mathrm{G_a} = \frac{1}{\mathrm{Z}} \sum_{\mathrm{x}=1}^{\mathrm{z}} \left(\frac{\mathrm{S}\rho_{\mathrm{x}}}{\rho_{\mathrm{x}} - 1}\right) \tag{9}$$

Equation (6) links $\mathrm{P_t}$ to ρ divided by its standard error, whilst Equation (7) relates $\mathrm{P_a}$ to a transformed ρ. Equation (8) computes $\mathrm{G_t}$ as an average of ratios involving ρ_{x} and their standard errors, weighted by Z. Equation (9) calculates $\mathrm{G_a}$ as an average of ratios involving S and ρ_{x}, weighted by Z. These equations are used in evaluating the null hypothesis (H_0) for cointegration.

3.3.4 | Estimation of the CS-ARDL Approach

The cross-sectional ARDL Chudik and Pesaran (2015) is employed to conduct comprehensive long- and short-term evaluations. When assessed through the AMG and MG strategies, this method demonstrates superior resistance to problems such as Cross-sectional Dependence (CSD), potential endogeneity, SH coefficients, and unit root issues. In addition, Saud et al. (2019) confirm its ability to manage unseen common factors with skill. The comprehensive Equation for CS-ARDL has been described as follows:

$$\mathrm{ET_{xt}} = \alpha_0 + \sum [r = 1\mathrm{tov}] \left(\lambda_{\mathrm{xt}} * \mathrm{ET_{xt-}}_r\right) + \sum [r = 0\mathrm{tov}] \left(\beta_{\mathrm{xt}} * \mathrm{P}_{\mathrm{t}-r}\right) + \sum [r = 0\mathrm{to}3] \mathrm{Z}_{\mathrm{t}-r} + \varepsilon_{\mathrm{xt}} \tag{10}$$

The Equation models the variable $\mathrm{ET_{xt}}$ based on its past values, the past values of another variable P, and contributions from a variable Z spanning three periods. The intercept α0 represents the base value of $\mathrm{ET_{xt}}$ without influences. Coefficients λ_{xt} and β_{xt} weight the influence of past values of ET and P, respectively. The term $\varepsilon_{\mathrm{xt}}$ captures unexplained variability in the model. In this context, (P) represents many independent factors, including MM, REC, FM, DGI, FDI, and CEI. We also use advanced robustness tests, AMG, and Common Correlated Effects Mean Group, referred to as CCEMG, which is in line with the recommendations of Schoch et al. (2012). These procedures, nonstandard statistical paradigms like MG (Mean Group) and PMG (Pooled Mean Group), give more credible findings because they skillfully circumvented challenges such as variable gradients, CSD, and unit root discrepancies.

4 | Results and Discussion

This section of the research is used to depict the results of this study. The statistical summaries, CSD, unit root analysis, and slope variance are discussed in the study. We then apply the 1st and 2nd generation Westerlund and Pedroni bootstrap cointegration analytical method to test long-term relationships. The next stage of this development results in the CS-ARDL analyses and ends with the AMG and CCEMG robustness tests (Irfan et al. 2022). As Figure 3 demonstrates, cross-country differences in the key determinants are noted in the Cleveland dot plots with mineral markets (MM), renewable energy consumption (REC), energy transition (ET), and financial markets (FM). These visualisations indicate an excellent difference between economies; the rate of sustainable development is not the same. Developing economies like India, China, and Indonesia have shown significant developments in renewable use and the use of minerals before being restricted by financial inefficiencies and carbon intensities. Conversely, the performance of developed economies such as Australia, Canada, and Norway remains steady in terms of ET, which is facilitated by the well-developed governance systems, better financial security, and the prompt adoption of digital governance solutions in the resource management systems. The visual demonstration reinforces the empirical findings that nations that have evolved institutional and financial frameworks have an easier and quicker time adopting sustainable energy frameworks.

These observations provide localised and practical suggestions in policymaking. The established economies must centralise their advancement in transition by adding to their investments in state-of-the-art clean technologies, such as green hydrogen, battery storage, and a digital energy grid, and bolster carbon pricing systems and the existence of emissions trading. However, third-world countries, in turn, require specific institutional changes to

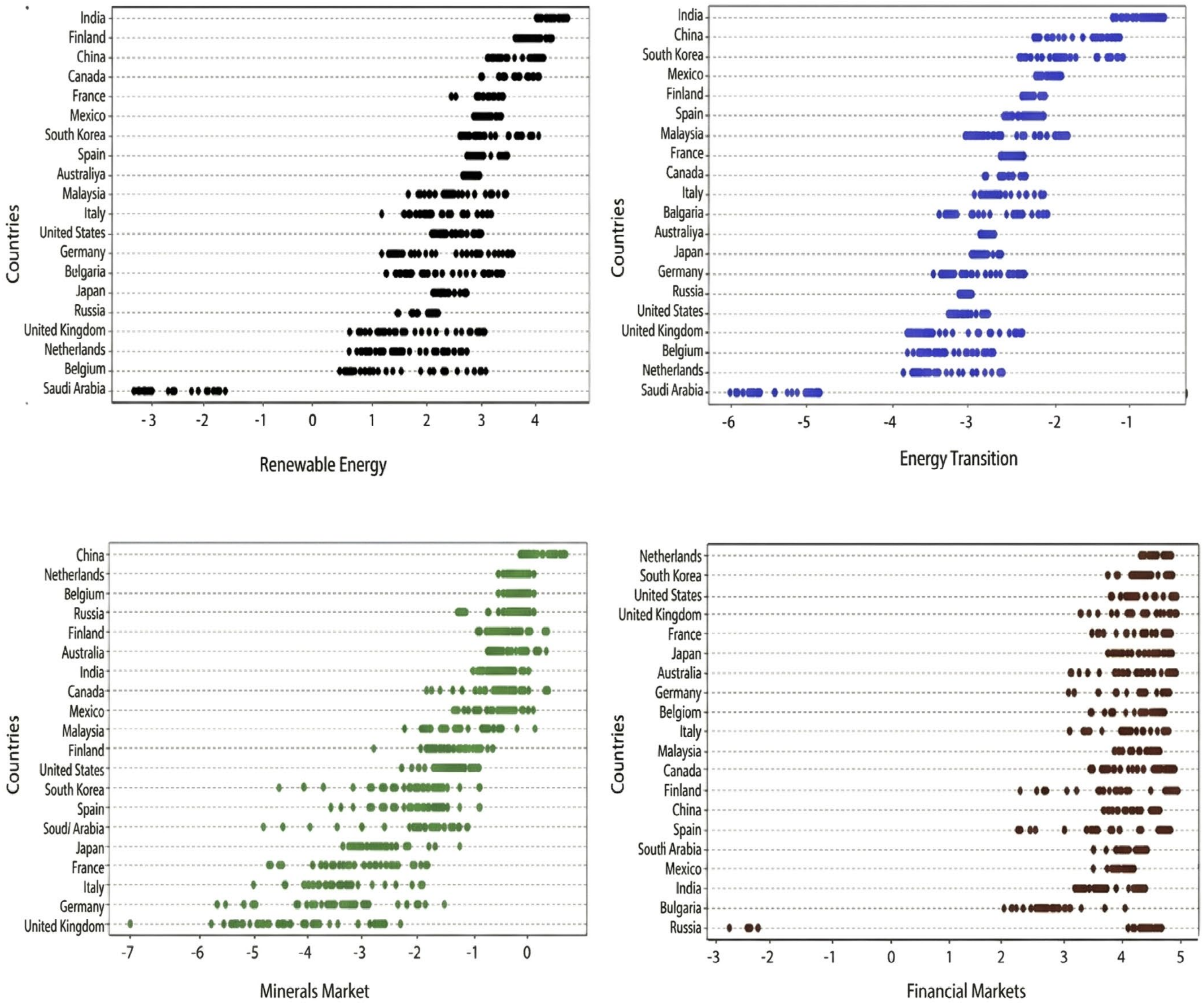

FIGURE 3 | Cleveland dot plot.

welcome green foreign direct investment (FDI), reverse unsustainable mining policies, and implement financial assistance for green projects. The policy should focus on environmental protection, local capacity-building, and good mining governance in African and South American countries with mineral deposits. In the meantime, Asian economies should strengthen their regulatory structures and make their energy systems more efficient to decrease reliance on fossil-based energy and increase the use of renewables.

Combining the outcomes of the dot plot and the econometric analysis gives a better idea of the correspondence between the visual patterns and the statistical evidence. Those countries with good MM performance scores and high DGI values portray faster ET development, and the argument in the study is justified, which is that digital governance and mineral efficiency are essential facilitators of sustainability. This visual and quantitative evidence complements a valuable pointer to the need to match financial innovation and digital governance and resource management strategies to enable environmental and economic balance.

To prepare ourselves to analyse the variables, Table 1 categorises the variables of interest, explaining their designations, measuring scales, expected results, and sources. Table 2 shows the statistical summaries based on a dataset of 822 nation-year data points of 20 major mineral-exporting countries from 1990 to 2023. The collective values (as per Model 3) of ET, FM, REC, DGI, and MM stand at −2.742, −0.408, 0.748, 0.520, and −1.480, respectively. The range of fluctuations of these metrics is 0.080 to 1.405. In closer analysis, Model 1 has higher ET and MM mean values than Model 2. The developed territories are, however, more fluctuating than the emergent ones. The fusion of these visual representations and the described statistics gives us a comprehensive view of the information positioning, which preconditions us to further analytical and profound studies. The results of Breusch-Pagan and Pesaran CD tests have been used to assess the cross-sectional dependence (CSD) of assessment panel countries, and the results have been tabulated in Table 3. The findings strongly indicate that such a CSD is present, just as is the case with the null hypothesis that a CSD exists that has been passed. It represents the interdependence of mineral-exporting economies, which was brought about by global digital contagion, regional relationships, and globalisation (Alwerfalli 2022). Table 4 shows Slope Homogeneity (SH) test results. These tests affirm the importance of slope heterogeneity in coefficients, which rejects the fact that there are consistent slopes.

These tests show a firm slope heterogeneity amongst the coefficients, refuting that homogeneous slopes are dominant. This makes the issue of stationarity of interest to the investigation. According to modern studies, Rehman et al. (2023), advanced unit root analysis, like CIPS and CADF, is applied regarding the identified CSD and slope changes. Table 5 shows the outcomes of the investigation of the inherent or initial stationarity of the investigated variables. The next step is the long-term interrelation between the variables. These long-term relationships are reinforced by the cointegration *t*-tests described in Table 6. The null hypothesis of non-cointegration is not maintained in metrics like G_t, G_a, P_t, P_a, and so on, which shows that the variables in the dataset have a significant interrelationship.

The output of the CS-ARDL model (in Table 7) that is backed by AMG and CCEMG robustness tests (in Table 8) indicates that substantial correlation exists between mineral markets (MM), financial markets (FM), renewable energy consumption (REC), digital government index (DGI), foreign direct investment (FDI), and carbon emission intensity (CEI). The mineral market (MM) has been found to have significant positive impacts on energy transition (ET) in short and long-run estimates, with positive measures of 0.49 and 0.42, respectively, showing that the growth of mineral resources positively influences the transition to sustainable energy systems. The outcome is not novel because researchers state that renewable energy sources, including solar panels, batteries, and wind turbines, require minerals like lithium, cobalt, and nickel in their production (Hodgkinson and Smith 2021; Lei 2021; Siklos 2022). The difference in the coefficients between the developed economies is a little higher; this means that developed countries are more technologically competent, have stronger environmental policies, and a strong institutional framework that enables them to convert mineral wealth into renewable energy investments more efficiently. This association supports the applicability of MM to SDG 7 (Affordable and Clean Energy) and the opportunities to achieve low-carbon growth goals.

On the contrary, the financial market (FM) has negative short-run and long-run coefficients, implying that financial growth will tend to spend money on the energy-intensive and industrial sectors rather than on the direct contribution to the support of green investments. This aligns with the findings of Saud et al. (2019) and Irfan et al. (2022), who discovered that financial development, which is not coupled with environmental governance, can strengthen the relationship between fossil fuel dependency and increasing carbon emissions. However, well-developed policy and regulatory provisions can and should enable financial markets to contribute to renewable energy use and digitalization. This means that a conditional relationship prevails, i.e., only in the presence of stringent environmental policies or specific green financial instruments such as sustainability-linked loans, green bonds, and climate-focused

TABLE 2 | Summary statistics.

	Model 1					Model 2					Model 3				
Variables	***N***	**Mean**	**SD**	**Min**	**Max**	***N***	**Mean**	**SD**	**Min**	**Max**	***N***	**Mean**	**SD**	**Min**	**Max**
ET	245	−2.19	0.78	−3.45	−0.68	578	−2.98	0.86	−6.01	−1.17	822	−2.74	0.91	−6.01	−0.67
MM	245	−0.54	0.49	−2.23	0.39	578	−1.87	1.47	−7.25	0.70	822	−1.48	1.40	−7.25	0.70
FM	245	−0.66	0.69	−3.89	−0.16	578	−0.30	0.25	−1.40	−0.02	822	−0.40	0.46	−3.89	−0.02
REC	245	1.02	0.45	0.09	1.79	578	0.62	0.80	−2.18	1.64	822	0.74	0.74	−2.18	1.79
FDI	245	0.11	0.63	−2.58	1.49	578	0.14	0.67	−3.13	1.94	822	0.13	0.66	−3.13	1.93
CEI	245	0.39	0.06	0.19	0.51	578	0.37	0.10	0.10	0.79	822	0.38	0.09	0.10	0.79
DGI	245	0.52	0.07	0.42	0.62	578	0.51	0.08	0.40	0.63	822	0.52	0.08	0.41	0.62

Note: Model 1 focuses on developing economies, whilst Model 2 targets developed countries. Finally, Model 3 encompasses the complete study sample.
Source: Calculated by the authors.

TABLE 3 | Breusch-Pagan and Pesaran CSD test results.

Variables	Model 1 (developing economies)		Model 2 (developed economies)		Model 3 (developing & developed economies)	
	Breusch-Pagan LM	Pesaran CD	Breusch-Pagan LM	Pesaran CD	Breusch-Pagan LM	Pesaran CD
ET	49.10***	−0.61	49.0***	4.73***	53.10***	−0.36
MM	168.9***	8.51***	506.3***	12.11***	444.20***	28.64***
FM	54.0***	−0.74	234.0***	13.03***	180.83***	5.27***
REC	102.3***	−0.54	124.9***	1.50	127.21***	−1.69*
FDI	53.0***	3.16***	278.44***	6.82***	187.68***	17.02***
CEI	79.0***	0.83	342.49***	0.26	292.02***	2.69***
DGI	65.2***	2.45***	300.12***	5.38***	250.78***	4.98***

Note: The significance levels are as *** for 1%, ** for 5%, and * for 10%.

TABLE 4 | Results of SH analysis.

Variables	Model 1 developing economies		Model 2 developed economies		Model 3 developing + developed economies	
	Test value	Prob.	Test value	Prob.	Test value	Prob.
Delta (Tilde)	10.7***	0.00	17.0***	0.00	22.57***	0.00
Delta (Adj.) (Tilde)	12.4***	0.00	19.6***	0.00	26.06***	0.00

Note: The degree of significance is indicated as follows: 0.01, 0.05, and 0.10.

TABLE 5 | CIPS and CADF unit root test results.

Variables	Model 1 (CIPS/CADF) $I(0)/I(\mathrm{I})$	Model 2 (CIPS/CADF) $I(0)/I(\mathrm{I})$	Model 3 (CIPS/CADF) $I(0)/I(\mathrm{I})$
ET	−2.18/−5.29***	−2.18/−5.29***	−1.97/−6.15***
MM	−2.72/−6.12***	−2.72/−6.12***	−2.75/−6.17***
FM	−2.98/−5.49***	−2.98/−5.49***	−3.38/−5.96***
REC	−1.19/−5.49***	−1.19/−5.49***	−2.33/−6.17***
FDI	−4.52/−6.09***	−4.52/−6.09***	−4.39/−6.19***
CEI	−2.55/−6.19***	−2.55/−6.19***	−2.57/−5.88***
DGI	−1.47/−5.70***	−1.47/−5.70***	−1.65/−5.85***

Note: Model 1 in Table 5 focuses on the digital landscape of developing countries, whilst Model 2 explores developed countries. Finally, Model 3 serves as an aggregate, encompassing the entire study sample. Significance levels are denoted with *** for 1%, ** for 5%, and * for 10%.
Source: Based on the authors' calculations.

funds, can financial growth lead to sustainability. As a result, financial policies will be tightened, and environmental performance standards will be implemented by the policymakers so that financial deepening is driven by renewable infrastructure and digitalisation and not the factors that cause ecological degradation.

Another positive and significant impact on ET is also determined in the study, renewable energy consumption (REC) and digital government index (DGI). It is imperative to mention that integrating renewable and digital transformation is a continuous and extensive influence on making energy more sustainable. The benefits of the increased introduction of REC are significant increases in ET, which attest to the findings of Suwa et al. (2021), Liu et al. (2016), and Lévy and Robinson (2017) that the renewable energy source is one of the primary supporters of emission reduction and energy security in the long term. On the same note, the affirmative effect of DGI substantiates the arguments by Chudik and Pesaran (2015), who found that digital governance improves institutional transparency and efficiency. The enhanced digital systems allow governments to control the energy systems better, allocate resources, and be accountable

TABLE 6 | Pedroni and Westerlund cointegration test results.

Variables	Model 1	Model 2	Model 3
Stat.	**Prob.**	**Stat.**	
Pedroni cointegration test			
Modified Phillips-Perron t	1.623*	0.054	2.312**
Phillips-Perron t	−3.045***	0.000	−4.857***
Augmented Dickey-Fuller t	−1.815**	0.024	−1.407*
Westerlund cointegration test			
Variance ratio	−4.519***	0.000	−2.963***
Westerlund Bootstrap cointegration test			
G_t	−4.201***	0.003	−5.301***
G_a	−7.620***	0.000	−11.670***
P_t	−10.455***	0.000	−9.495***
P_a	−12.380***	0.000	−13.770***

Note: Model 1 in Table 6 pertains to developing countries, whilst Model 2 focuses on developed countries. Model 3 encompasses the entire set of countries studied. Significance levels are denoted as *** for 1%, ** for 5%, and * for 10%.

for environmental performance, thus meeting SDG 9 (Industry, Innovation, and Infrastructure). Besides, foreign direct investment (FDI) positively influences ET, which is consistent with the findings of Wang et al. (2023) and Ngo et al. (2022), who find that FDI contributes to transferring technology and increasing international cooperation in energy transition towards cleaner energy.

Lastly, the results indicate that the intensity of carbon emission (CEI) is negatively correlated to ET in all models, implying that economies with a heavier carbon footprint experience greater challenges with implementing sustainable energy policies. This negative correlation confirms the results of Saud et al. (2019), who felt that it is challenging to transition to the use of green energy due to the carbon-intensive industries. The findings indicate the relevance of a comprehensive policy that would promote the utilisation of carbon price, emission trading, and energy-efficient policies, particularly in mineral-based economies. These results confirm that long-term energy security and environmental resiliency are based on sustainable management of minerals, green financial reform, digitalisation, and low-carbon policy models. Such an integrated solution would not only make the world's transition to energy a much faster one but also affect the SDG 7 (Clean Energy), SDG 9 (Innovation and Infrastructure), and SDG 13 (Climate Action) directly.

5 | Conclusions and Policy Recommendation

This is the primary research on finance and MM, which concerns other facets of sustainable energy practises like CEI, FDI, clean energy, and DGI. The scholar concentrates on the 20 major mineral-exporting economies and depends on panel data, 1990–2023. This sample was further divided into two structures to learn about the developing and the well-developed countries. Potent insights were developed using high-level statistical methods: cross-sectional AMG, cross-sectional CCEMG, and cross-sectional ARDL. The techniques effectively overcome the problem of slope heterogeneity, CSD, and endogeneity. It has been discovered that markets that address the concerns of minerals are significant players that can encourage sustainable energy and clean and low-carbon energy production. Conversely, FM and the long-run liberal relationship between FM and ET are likely to be inverted. Clean energy measures and FDI are other measures that positively influence sustainable ET. The developed countries are increasingly aligning their digital operations with the environmental sustainability agenda.

The statistics have shown an increasing demand for minerals, especially with the increase in power generation through clean energy. It is also spearheaded by the augmented manufacturing of electric vehicles (EVs), which are of a renewable nature and cause a demand for specific minerals like copper, lithium, nickel, and graphite. In fact, using such discoveries, we suggest some policy implications for the mineral-exporting countries. First, the paper identifies the significance of minerals like lithium, nickel, graphite, and copper, which will be very important in generating ET and low-carbon power. That is why policymakers must focus on developing successful MM and its incorporation in REC projects to meet sustainability goals. Second, because FM will probably damage the energy efficiency, there is a need to implement measures to enable the smooth use of energy in the financial industry. Finally, DGI, REC and FDI are potent predictors of ET, especially in the developed nations. The findings indicate the importance of distinguishing sustainability policies according to the differences in the impact of digital governance (DGI) across economies and foreign direct investment (FDI). Digital governance is an enchantment of transparency, innovation, and renewable integration in the developed world. In developing countries, FDI has been a significant source of clean energy infrastructure and technology flow. The evidence-based approach is in tandem with the larger objectives of SDG 7 (Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). Inclusiveness and regional adaptation should be considered in future policies to ensure that the digital transition and sustainable investment will lead to a resilient, equal, and climate-receptive global energy transition.

Regarding the export of minerals, the emerging economies should develop access facilitation methods to provide sustainable financial development and encourage ET and efficient consumption. This study project has certain limitations. To improve, one of the options that can be chosen is to exclude other

TABLE 7 | CS-ARDL test results.

	Model 1		Model 2		Model 3	
Variables	**Coefficient**	**Standard errors**	**Coefficient**	**Standard errors**	**Coefficient**	**Standard errors**
Long-run estimates						
MM	0.420***	0.076	0.619***	0.036	0.423***	0.041
FM	−0.493***	0.025	−0.258***	0.024	−0.312*	0.187
REC	1.108***	0.046	1.417***	0.126	1.116***	0.043
FDI	0.122***	0.024	0.218	0.358	0.187***	0.070
CEI	−0.831***	0.106	−0.173*	0.090	−0.457	0.342
DGI	0.250***	0.032	0.311***	0.025	0.285***	0.034
Short-run estimates						
ΔMM	0.450***	0.141	0.502***	0.147	0.493***	0.071
ΔFM	−0.586***	0.026	−0.301***	0.019	−0.486***	0.016
ΔREC	1.073***	0.047	1.311***	0.097	1.261***	0.122
ΔFDI	0.318	0.392	0.723***	0.063	0.523	0.363
ΔCEI	−0.826***	0.110	−0.171*	0.091	−0.260	0.213
ΔDGI	0.205***	0.026	0.198*	0.030	0.220***	0.022
p	0.002		0.000		0.000	
ECM (−1)	−0.938		−0.968		−0.933	

Note: Model 1 in Table 7 is designed to analyze developing economies, Model 2 targets developed countries, and Model 3 includes the complete dataset for the study. Levels of statistical significance are indicated as follows: *** signifies a 1% level, ** indicates a 5% level, and * represents a 10% level.
Source: Calculations by the authors.

TABLE 8 | Robustness' test results.

	AMG		CCEMG		AMG	
MM	1.093*** (0.198)	0.927*** (0.072)	1.029** (0.047)	0.904*** (0.174)	1.025** (0.438)	0.9001*** (0.152)
FM	−0.673*** (0.274)	−0.349** (0.143)	−0.429*** (0.027)	−0.318*** (0.057)	−0.543*** (0.215)	−0.303*** (0.024)
REC	1.082*** (0.028)	1.074*** (0.042)	1.214*** (0.064)	1.277*** (0.118)	1.135*** (0.036)	1.103*** (0.041)
FDI	0.531*** (0.049)	0.613*** (0.064)	0.867 (0.669)	0.876*** (0.322)	0.606 (0.413)	0.816* (0.476)
CEI	−0.466* (0.301)	−0.236 (0.203)	−0.189* (0.111)	−0.147 (0.095)	−0.293 (0.282)	−0.235 (0.298)
DGI	0.315* (0.173)	0.238 (0.089)	0.367** (0.153)	0.348** (0.089)	0.323** (0.169)	0.339* (0.092)
Const.	−2.385 (2.933)	−1.033 (1.358)	−3.444** (1.434)	−1.671 (2.391)	−2.386*** (0.867)	−1.244*** (0.303)
Wald-test	111.635	1352.920	402.890	1541.990	618.350	1771.030
RMSE	0.015	0.010	0.017	0.009	0.017	0.010
p	0.000	0.000	0.000	0.000	0.000	0.000
N	245	245	573	573	822	822

Note: Standard errors have been presented within parentheses. Model 1 in Table 8 focuses on developing countries, Model 2 is specific to developed countries, and Model 3 encompasses the whole dataset for the research work. Significance levels are denoted as follows: *** for a 1% level, ** for a 5% level, and * for a 10% level.

econometric strategies, non-linear models, or causality that can provide a more analytical understanding of resource-rich economies. Moreover, the study does not involve comparative research in various regions of the globe; thus, the research findings and implications may not be universal. Going by this, future studies can be interested in the empirical studies that extend across a broader geographical or economic context. It would bring more empirical rigor to policy recommendations and make them more broadly applicable than before to provide a more comprehensive view.

Author Contributions

Hamza Akram: data curation, investigation, methodology, supervision, writing – review and editing. **Jinchao Li:** formal analysis, software, supervision, validation, writing – original draft, writing – review and editing. **Muhammad Ashar Asdullah:** data curation, methodology, writing – review and editing. **Muhammad Salman Shabbir:** conceptualization, methodology, validation, writing – original draft, writing – review and editing. **Waqas Ahmad Watto:** methodology, validation, writing – review and editing. **Tuba Rasheed:** data curation, investigation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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