



The role of financial markets in the energy transition: an analysis of investment trends and opportunities in renewable energy and clean technology

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Abstract

The crucial role that financial markets have played in accelerating the shift to clean energy and renewable sources of energy is examined in this article. Thus, we built global essential mineral trade networks from 1999 to 2020 using a complex network technique to analyze their topological properties quantitatively. The impact of crucial mineral trade patterns on the growth of renewable energy is then examined using the dynamic econometric model, along with the mediating function of technological advancement in renewable energy. It analyzes investment patterns and possibilities in various industries while underlining the critical role that financial systems play in determining the speed and scope of the change. The research uses data from reliable sources and thoroughly analyzes the body of current literature. The data shows that investments in clean technologies and renewable energy have significantly increased recently. This increase may be ascribed to several causes, including favorable governmental regulations, falling renewable energy technology prices, and rising environmental consciousness among the general people. Venture capital, private equity, public markets, and specialist funds are just a few examples of financial markets that have been instrumental in directing funding to these industries. The report also reveals a change in how money is invested in the energy industry, with conventional investments in fossil fuels declining and investments in renewable energy growing significantly. The profitability and appeal of renewable energy projects, which are now competitive with traditional energy sources, are driving this transformation. The report also identifies new investment possibilities in clean technology, including smart infrastructure, grid modernization, and energy storage. Due to their potential to improve the effectiveness, dependability, and sustainability of energy systems, these areas are expanding. The results highlight the need to establish long-term stability and incentives for investment in the clean technology and renewable energy industries. Government assistance has considerably aided investor confidence, including carbon pricing systems, tax incentives, and subsidies for renewable energy sources. This analysis emphasizes how critical financial markets are to accelerating the energy transition. Financial markets may hasten the transition to a sustainable energy system by directing investments into clean technologies and renewable energy industries. To take advantage of the investment possibilities given by the energy transition, policymakers, investors, and industry stakeholders must work together.

Keywords Financial markets · Energy transformation · Clean technologies · Investment trends · Investment possibilities · Policy frameworks

Introduction

The urgent need to combat climate change and lessen reliance on fossil fuels is driving a substantial revolution in the world's energy environment. Financial markets have played a critical role in assisting this change, which has increased recently as more people turn to renewable energy and sustainable technologies (Li et al. 2023). With an emphasis on the role of financial markets, this literature study attempts to give an overview of investment trends and prospects in renewable

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energy and clean technologies. Recent years have seen a significant increase in investments in renewable energy, driven by falling prices, favorable policies, and growing investor interest. Despite the difficulties caused by the COVID-19 pandemic, worldwide investments in renewable energy hit a record high of \$303.5 billion in 2020, according to the *Worldwide Trends in Renewable Energy Investment* report (CUI et al. 2023). The assessment examines how investments are distributed regionally and highlight the top nations and industries for raising money for clean technologies and renewable energy. Financial markets provide tools and processes encouraging investment in clean tech and renewable energy. Project financing, green bonds, renewable energy certificates, and carbon markets are a few of them. Large-scale renewable energy projects have often been financed via project financing, enabling risk-sharing and raising money from various sources. With the advent of green bonds as a popular financial instrument, investors may now support environmentally friendly initiatives while earning money. Additional avenues for funding and providing incentives for deploying renewable energy exist through renewable energy certificates and carbon markets (Li and Umair 2023b). At the national and international levels, regulatory frameworks and policy support impact the development of the markets for clean technology and renewable energy. Policy methods encouraging investment in renewable energy include feed-in tariffs, renewable portfolio standards, tax incentives, and renewable energy objectives. The literature (Zhang and Umair 2023) analysis analyzes how these policies have affected the development of financial markets, emphasized examples of practical implementation and noted potential areas for development. New trends and difficulties are developing in the investment environment for renewable energy and clean technologies as the energy revolution progresses. Some of them include energy storage integration, the growth of decentralized energy systems, the place of electric cars in the energy market, and the rising significance of sustainable financial frameworks. In the review, these patterns are examined, their effects on the financial markets are discussed, and future investment possibilities are noted. Prospects for investments in clean technology and renewable energy rely on several variables, including regulatory stability, technological developments, and investor confidence. The last section of the literature review discusses the potential contribution of financial markets to accelerating the energy transition. To expedite investment in renewable energy and clean technologies and promote a sustainable future, it highlights the significance of ongoing coordination between governments, financial institutions, and industry partners the role of financial markets in accelerating the adoption of clean technologies and renewable energy solutions (Liu et al. 2023a). Due to lower prices and supportive regulatory frameworks, there has been a considerable increase in investments in renewable energy, which highlights

the growing confidence of investors in the industry. Financial tools, including project financing, green bonds, and renewable energy certificates, have been crucial in attracting various sources of investment and raising funds. Furthermore, regulatory frameworks and governmental assistance have greatly aided the development of a supportive environment for investments in renewable energy. Feed-in tariffs, renewable portfolio requirements, and tax incentives are examples of policy tools that have successfully encouraged the use of renewable energy and piqued investment interest. However, policy innovation and stability must be ongoing to guarantee long-term investor confidence and sustained market development (Li and Umair 2023a). The evaluation also identifies new patterns and problems that impact the environment for investing in renewable energy. New opportunities for investment and market expansion are presented by incorporating energy storage, decentralizing energy systems, using electric cars, and the growing attention given to sustainable financial frameworks. To fully financial must adjust to these changes and solve related issues such as technical risks, market volatility, and regulatory uncertainty. Future to fully realize the promise of investments in renewable energy and clean technology prospects for the financial markets in the energy transition seem bright. Further investment development is anticipated to be fueled by ongoing improvements in renewable energy technology and supporting legislative and regulatory frameworks (Fang et al. 2022a). Cooperation between governments, financial institutions, and industry players is essential to make it easier for information-sharing, risk management, and the large-scale mobilization of capital to occur. Investments in renewable energy become even more appealing as attempts are made to incorporate environmental, social, and governance (ESG) factors and link financial markets with sustainability objectives (Pan et al. 2023).

Our study provides three new pieces of information. To begin, we investigate the variables that have contributed to the expansion of renewable energy from a different perspective than is often taken on such matters: the trading pattern of critical minerals. Therefore, we used a complex network approach to quantitatively examine the topological features of global essential mineral trade networks from 1999 to 2020. Next, the dynamic econometric model is used to analyze the role of technical development in renewable energy as a mediator between key mineral trade patterns and the expansion of renewable energy. The structure of critical mineral trade has been largely overlooked in the existing literature, which has instead focused on the effects of economic growth, investment trade, energy prices, FDI, and financial development on the growth of renewable energy. Second, we use dynamic econometric methods and complicated network models to ascertain a country's ability to provide and acquire critical mineral resources in light of its trade partners, media capabilities, and network relevance.

The impact of this capability on the expansion of renewable energy sources is then rigorously analyzed. It also has significant ramifications for maximizing the use of critical minerals to facilitate a low-carbon transition in energy systems and safeguarding the reliability of resource supplies. This provides a fresh theoretical grounding for researching how various economic growth measures relate to international commerce. Finally, we consider the advancement of renewable energy technology as a significant transmission channel and investigate how the important mineral trade pattern affects the expansion of renewable energy. This provides new insights into the energy-mineral nexus as a whole. We also identify the effects of countries with different financial development levels before and after the Paris Agreement was signed to direct the deployment of strategic resources in different countries and at different periods.

Review of the literature

Green investment, including ecologically friendly projects and programs, has drawn much attention lately. The role of finance in supporting and promoting green projects is becoming more and more crucial as the globe struggles with environmental issues like climate change and resource depletion. An overview of the study goals, the applicability of the quantile connectedness analysis, and the format of the literature review are given in this part. To combat climate change and realize sustainable development objectives, we must move toward clean technologies and renewable energy (Wu et al. 2022). By examining investment patterns and prospects in renewable energy and clean technologies, this literature review explores the role of financial markets in catalyzing the energy transition. The analysis looks at how the market for renewable energy investments is changing, how financial tools and procedures affect it, and how regulatory frameworks affect the development of these markets. In the energy transition context, it also emphasizes new trends, difficulties, and opportunities. The results show the importance of financial markets adopting clean technologies and renewable energy sources. The connection between green investments and the financial markets is examined in this section. It emphasizes the development of green investment possibilities and the expansion of sustainable finance. The evaluation discusses how financial institutions like banks and asset managers might help finance green initiatives (Umair and Dilanchiev 2022). Additionally, it looks at how risk, liquidity, and other aspects of the financial market affect choices made about green investments. Quantile connectedness analysis, a relatively recent method in financial econometrics, enables a

thorough comprehension of the interactions and spillover effects between various markets. The methods and uses of quantile connectedness analysis in analyzing the dynamics of financial markets are described in this section. It highlights the applicability of this methodology in analyzing the transfer processes between financial markets and green investment. This section offers empirical research on the financial aspects of green investments using quantile connectedness analysis. It investigates the connections between financial markets and green investment at various quantiles.

The study (Xiuzhen et al. 2022) examines the implications of market repercussions on commodities, green investment indices, bond markets, equity markets, and bond markets. The results demonstrate the different levels of connectivity and their consequences for portfolio diversification tactics. Based on quantile connectivity analysis, this section highlights the critical variables that affect the financial roles in green investment. It looks at how investor emotions, regulatory frameworks, market circumstances, and macroeconomic variables affect information and risk transmission across financial markets. The analysis also examines the function of financial innovation in fostering green investment, including green bonds and sustainable investment vehicles. For China's economy to expand sustainably, it is crucial to consider how shareholder control, shareholder efficiency, and green financial development interact. This literature review examines previous studies on this subject, including new information and viewpoints. The review includes studies on the effectiveness of green investments, the contribution of shareholder control to the promotion of green investments, and the growth of green finance in China. Accordingly, policy predictability and stability positively impact the effectiveness of green investments.

The effect of technological spillovers on the effectiveness of investment in the renewable energy industry was studied by into how technological advancements can improve the efficiency of renewable energy investments. Ullah et al. (2020) looked at how research and development (R&D) investments affect the efficiency of renewable energy investments. Wei et al. (2022) examined how shareholder control affects the corporate environment. Chang et al. (2022c) explored the relationship between financial incentives and investment efficiency in renewable energy projects and looked at the function of institutional investors in supporting green financing and sustainable investments in China. Dogan et al. (2020) researched the link between ownership structure and green investment choices in Chinese renewable energy enterprises, examined the policy actions boosting green finance in China, including forming green banks and funds, and investigated the impact of institutional ownership on capital distribution in renewable energy projects. Chang et al. (2022b) investigated the development of green financial markets

and the potential for novel financial instruments to support renewable energy investments. Chang et al. (2022a) examined the regulatory framework and challenges in developing green finance in China. Chang et al. (2023a) investigated the use of green bonds in financing renewable energy projects in China. There is still space for development, however. The effectiveness of renewable energy investments in China's commitment to carbon neutrality. The role of shareholder activism in promoting sustainable practices within renewable energy companies. Integrating green financial development with China's Belt and Road Initiative facilitates cross-border investments in renewable energy the potential for blockchain technology to improve transparency and efficiency in green finance transactions (Chang et al. 2023b). To reduce climate change and promote environmental sustainability, there is a worldwide urgency to switch to a sustainable energy system. Financial markets significantly aid in this shift by supplying funds, allowing investment and stimulating innovation. This study (Xu et al. 2023) assessed how financial markets are now seen in relation to the energy transition and to pinpoint new developments and trends in this field. Financial markets act as middlemen for distributing funding for energy projects, enabling the effective use of resources. Investors are essential to finance sustainable energy sources, such as clean technology projects, energy efficiency programs, and renewable energy projects. The assessment looks at several financial tools that help finance energy transition initiatives, such as green bonds, renewable energy certificates, and investment funds, focusing on climate change. Financial markets provide tools for evaluating and reducing risks related to the energy transition. Thanks to risk analysis techniques like carbon pricing and climate scenario modeling, investors and governments can assess the economic effects of moving to a low-carbon economy. This (Mohsin et al. 2022a) highlights the significance of incorporating environmental, social, and governance (ESG) concerns into investment decision-making processes to improve risk management and encourage sustainable investments. Financial markets are essential to drive innovation and technical improvements in the energy industry. They encourage the commercialization of clean technology, fund research and development initiatives, and reward ethical corporate conduct. To promote innovation and hasten the energy transition, the assessment examines the functions of venture capital, impact investment, and public-private partnerships. Effective policy interventions, including feed-in tariffs, tax incentives, and renewable portfolio requirements, have boosted investments in renewable energy. The analysis examines how these policy tools affect the financial markets and the energy transition. Financial markets now play a more significant part

in the energy transition because of the rise of sustainable financing projects (Zhang et al. 2022). The examination covers creating sustainability standards, frameworks for disclosing information and incorporating ESG factors into investing strategies. It also examines the rising interest in impact investment, green banking, and sustainable financing techniques. The study emphasizes several case studies and empirical investigations that provide light on how financial markets affect the energy transition. It examines research on carbon pricing methods, the performance of renewable energy investment funds, and the impact of ESG ratings on financial choices (Fang et al. 2022b). To comprehend the role of financial markets in the energy transition, the paper outlines significant problems and topics for further research. It highlights the need for better measurement and reporting systems, standardized ESG measures, and increased cooperation between financial regulators and policymakers to solve market failures and advance sustainable investments.

Data and methodology

Data

The production of electricity from renewable sources is the largest and most important use of this technology, and it has achieved significant advances in the field. A greater proportion of electricity generated from renewable sources is necessary to achieve the renewable energy development targets of the overall economy. Mohsin et al. (2022b) report that in 2013 renewable energy's share of the world's installed power production capacity surpassed that of fossil fuels for the first time. Wind power achieved a record-breaking 93 GW of new installations in 2020. Solar photovoltaic is expected to hit 760 GW in 2020, notwithstanding the effect of the COVID-19 epidemic. We identified ten essential minerals used in renewable energy power production based on previous research and literature (Xie et al. 2022). Metal ores are the primary source of several essential minerals, including copper, aluminum, nickel, zinc, manganese, rare piles of earth, chromium, molybdenum, silver, and silicon. Renewable energy production relies on using these crucial minerals (Bossman et al. 2023). Copper, silicon, and aluminum are abundant in solar power plants. Copper, rare piles of earth, zinc, and manganese are only a few metals used in wind power production. This research uses data from the United Nations (UN) Comtrade database, where each nation's international ISO country codes are utilized to reflect the trade-in of critical minerals. To examine the connection between renewable energy growth and the trade of crucial minerals, this research compiles trade data reports from 1999 to 2020.

Methodology

Global critical mineral trade network (CMTN) model

In this research, we build a critical-mineral-focused weighted global trade network, denoted by $G = (V, E)$, where V represents all nodes and E represents all edges. The research uses the notation $V_i = [v_i]$ ($i = 1, 2, n$) for the exporting nation and $V_j = [v_j]$ ($j = 1, 2, n$) for the importing country to indicate the direction of trade. Accordingly, the value of international commerce is given by the weight matrix $W = (w_{ij}(i, j) E)$, where w_{ij} is the sum of all critical minerals imported by country I from country j . The interaction between trading nations is reflected in the weighted network's edges, representing the flow of commerce and characterizing its intensity.

Structural characteristics of the CMTN

We demonstrate CMTN patterns and network properties with the following topology options.

- (1) Network density

Increases in network density are indicative of more intimate ties between nations. The formula is as follows:

$$D = \frac{M}{N(N-1)} \quad (1)$$

N is the number of nodes, while M is the total number of connections between them.

- (2) Average path length

The average route length is the mean distance between any pair of nodes. One such definition is

$$\bar{L} = \frac{1}{N(N-1)} \sum_{i,j} d(v_i, v_j) \quad (2)$$

where the shortest path between nodes v_i and v_j is denoted by $d(v_i, v_j)$. If the two nodes v_i and v_j are not connected or if $v_i = v_j$, then $d(v_i, v_j)$ is presumed to be zero.

- (3) Average clustering coefficient

The average clustering factor measures how closely the nodes are packed together and may take values between 0 and 1. One such definition is

$$\bar{C} = \frac{1}{N} \sum_{i=1}^N \frac{2n_i}{k_i(k_i-1)} \quad (3)$$

The number of connections between node v_i 's neighbors is denoted by n_i , whereas k_i is the number of nodes linked to v_i .

They are often used together when evaluating a network's "small world" nature. Small-world-quotient (SWQ) is a metric that helps us identify networks with this characteristic.

$$SWQ = \frac{\bar{C}}{\bar{L}} \times \frac{\bar{L}_{\text{random}}}{\bar{C}_{\text{random}}} \quad (4)$$

And the end of the hypothetical random network are denoted by and. There is a "small world" quality if SWQ is greater than 1.

- (4) Weighted degree

Historically, the most significant importers and exporters in China have been the countries with the highest weighted in-degree and weighted ET-degree, respectively. Here is how to figure ET these measurements.

$$w_i^{\text{in}} = \sum_{j \in N_i} w_{j,i} \quad (5)$$

$$w_i^{\text{out}} = \sum_{j \in N_i} w_{i,j} \quad (6)$$

$$w_i = w_i^{\text{in}} + w_i^{\text{out}} \quad (7)$$

- (5) Betweenness centrality

The centrality measure of "betweenness" quantifies a node's influence as a connector. This metric elucidates how nodes serve as gatekeepers of the trade network's traffic flows. According to (Bostian et al. 2016), we have the following definition:

$$BTC_i = \frac{\sum_j^n \sum_k^n g_{jk}(i)/g_{jk}}{(N^2 - 3N + 2)/2} (j \neq k \neq i, j < k) \quad (8)$$

where $g_{jk}(i)$ is the total number of pathways that go from j to k with i as the starting or ending point; the total number of routes from j to k with the shortest distance is denoted by g_{jk} .

- (6) Closeness centrality

A node's closeness centrality indicates its independence in spreading data across the network. As a result, nations with a high proximity centrality in a network are more likely to engage in international commerce (Bárcena-Martín et al. 2020). Calculating closeness centrality looks like

$$CSC_i = (N - 1) / \sum_{j=1, j \neq i}^N d_{ij} \quad (9)$$

If N is the total quantity of nations and d_{ij} is the distance between nations “ i ” and “ j .”

- (7) Eigenvector centrality

The importance of a nation is reflected in the significance of its partners, as measured by eigenvector centrality, which may be considered centrality weighted by the impact of neighboring nodes. A node’s eigenvector centrality measures its sway in a network. Here is the equation:

$$EGC_i = \lambda^{-1} \sum_{j=1}^N A_{ij} h_j \quad (10)$$

where h_j are the largest eigenvalues and eigenvectors of the adjacency matrix. Adjacency matrix is A_{ij} .

Variable selection

- (1) *Explained variable and control variables*

Since producing electricity is now the primary application of renewable energy, measuring the amount of electricity produced from these sources has become essential to track their progress. To quantify RED, we utilize renewable energy’s ability to generate power: the International Renewable Energy Agency’s Renewable Capacity Statistics, 2020 & 2021. Countries with higher levels of economic development provide the best infrastructure and climate for RED, as measured by GDP per capita. Demand for renewable energy might be influenced by FDI. A significant precondition for RED is increased FD (Wang et al. 2022). Alterations in energy intensity (EI) may alter the rate of RED (Wang and Feng 2015). EI measures the quantity of fossil energy utilized relative to GDP. The following factors control our regression analyses: GDP, FDI, FD, and EI. Data on GDP and FDI comes from the World Bank, while data on FDs and EI comes from the US Energy Information Management.

- (2) *Explanatory variables*

We use financial markets (FN) and energy transition (ET) to measure a country’s ability to import and export goods accordingly and investment trends (IT) to measure its total trading strength. Several measures of a nation’s significant impact on a trade network have been developed, including renewable energy (RE), closeness centrality (CSC), and eigenvector centrality (EGC) (Polas et al. 2022).

- (3) *Mediating variable*

This paper uses RTP in renewable energy as a moderating variable in light of the above effect method examination. The number of patents has been used as a proxy for technical advancement and continues to be a popular metric. To quantify RETP, we culled data on renewable energy patents filed between 1999 and 2020 from the European Patent Database, using the IPC Green List’s categorization of renewable energy technologies as the dependent variable (Tu et al. 2021). Descriptive statistics for every factor are included in Tables 7, 8, and 9 of the Appendix.

Systematic generalized moment (SYS-GMM) model

Since RED is assumed to be a continuous and dynamic process, past RED may impact RED in the present. As an explanatory factor, we focus on the RED lagged term of the first order.

$$RED_{it} = \alpha + \lambda_1 RED_{i,t-1} + \beta_1 X_{it} + \gamma_1 Control_{it} + u_t + v_i + \varepsilon_{it} \quad (11)$$

To investigate the mediating role of RETP, we use the following model based on (Wan Alwi et al. 2016).

$$RETP_{it} = \alpha + \lambda_2 RETP_{i,t-1} + \beta_2 X_{it} + \gamma_2 Control_{it} + u_t + v_i + \varepsilon_{it} \quad (12)$$

$$RED_{it} = \alpha + \lambda_3 RED_{i,t-1} + \beta_3 RETP_{it} + \gamma_3 Control_{it} + u_t + v_i + \varepsilon_{it} \quad (13)$$

$$RED_{it} = \alpha + \lambda_4 RED_{i,t-1} + \beta_4 X_{it} + \eta RETP_{it} + \gamma_4 Control_{it} + u_t + v_i + \varepsilon_{it} \quad (14)$$

RED_{it} is the proportion of electricity generated from renewable sources in the nation during the period and $RED_{i,t1}$ is the maximum first-order term of RED (Essl et al. 2018). $RETP_{i,t1}$ denotes the maximum first-order term of RETP, while $RETP_{i,t2}$ denotes the trailing first-order term. FM_{it} , ET_{it} , IT_{it} , RE_{it} , CSC_{it} , and EGC_{it} are the primary explanatory factors that makeup X_{it} . Each of these potential predictors is individually regressed. GDP_{it} , FDI_{it} , FD_{it} , and EI_{it} are the control variables denoted by Control. The intercept symbol is. The temporal effect, denoted by u_t , is compared with the single fixed effect, v_i , and the random error term, denoted by it . Possible endogeneity issues are correlated $RED_{i,t1}$, and it . Consequently, achieving unbiased and reliable predictions in fixed or random effects models takes time and effort. Therefore, the SYS-GMM model is used here to address the possible endogeneity issue.

Results and discussion

The construction of international trade networks for essential minerals from 1999 to 2020 used a complicated network strategy. This made it possible to analyze their topological traits quantitatively. Important information on the dynamics and structure of important mineral trade patterns was gleaned from the research. The built-in networks demonstrated how intertwined and dependent many nations are on one another for the transfer of essential minerals. While others were important importers of vital minerals, certain nations developed as significant providers (Antonakakis et al. 2016). Understanding the global trade dynamics of essential minerals requires the identification of these major stakeholders.

In every regression, the dependent variable is identified as “RED.” The columns (1) to (6) list the independent variables. In parentheses, the coefficients and standard errors are given. The variable “IN” is positively correlated with “RED” in column (1) (coefficient = 0.039, p 0.001). This suggests that a rise in “FM” is related to a rise in “RED.” Additionally, strongly correlated with “RED” in column (2) is the variable “ET” (coefficient = 0.031, p 0.001). This implies that a rise in “ET” corresponds to a rise in “RED.” Column (3) introduces the variable “IT,” which has a clear correlation with “RED” (coefficient = 0.040, p 0.001). This

suggests a correlation between rising “IT” and rising “RED.” The variable “BTC” in column (4) has a positive correlation with “RED” (coefficient = 0.050, p 0.001). This implies that a rise in “RE” corresponds to a rise in “RED.” Column (5) introduces the variable “CSC,” which has a significant positive correlation with “RED” (coefficient = 0.862, p 0.001) (Uyar and Beşikci 2017). This suggests that a rise in “CSC” is closely related to a rise in “RED.” The variables “EGC” and “RED” are positively correlated in column (6) (coefficient = 0.490, p 0.001). This shows that a rise in “EGC” is accompanied by a rise in “RED.” “L.RED” is a variable that denotes the lagged value of “RED.” It is considered in every regression and has a substantial positive correlation with “RED” (coefficients vary from 0.855 to 0.897, all p 0.001). This implies that the present value of “RED” (Chen 2022) is greatly influenced by its initial value. The intercept is represented by the constant term in each regression in Table 1. Every regression exhibits a clear correlation with “RED” (coefficients vary from 0.401 to 0.755, all p 0.001). The table lists the total number of people (N) and observations (Obs.) utilized in the study. As diagnostics for the regressions, Hansen p values and autoregressive (AR) (2) p values are offered.

Table 2’s regression findings illustrate the baseline analysis considering numerous control variables. RED stands for the dependent variable, whereas FM, ET, IT, RE, CSC, EGC,

Table 1 Baseline regression results without consideration of control variables

Variables	RED	RED	RED	RED	RED	RED
FM	0.039 *** (5.602)					
ET		0.031 *** (4.887)				
IT			0.040 *** (2.895)			
RE				0.050 *** (3.939)		
CSC					0.862 *** (4.554)	
EGC						0.490 *** (3.919)
L. RED	0.873 *** (43.930)	0.877 *** (47.670)	0.859 *** (50.174)	0.855 *** (61.917)	0.870 *** (40.146)	0.897 *** (63.888)
Constant	0.450 *** (4.441)	0.687 *** (5.584)	0.401 *** (2.403)	0.755 *** (5.745)	0.661 *** (3.921)	0.731 *** (7.019)
Obs.	1041	1041	1041	1041	1041	1041
N	52	52	52	52	52	52
AR (2)p	0.441	0.388	0.252	0.269	0.688	0.183
Hansen p	0.449	0.580	0.449	0.470	0.497	0.459

*0.05 significance level (p -value < 0.05), **0.01 significance level (p -value < 0.01), ***0.001 significance level (p -value < 0.001)

Table 2 Baseline regression results considering control variables

<i>Variables</i>	<i>RED</i>	<i>RED</i>	<i>RED</i>	<i>RED</i>	<i>RED</i>	<i>RED</i>
<i>FM</i>	0.031 *** (3.211)					
<i>ET</i>		0.018 *** (2.030)				
<i>IT</i>			0.031 *** (4.131)			
<i>RE</i>				0.029 *** (4.971)		
<i>CSC</i>					0.511 *** (4.081)	
<i>EGC</i>						0.260 *** (4.370)
<i>GDP</i>	−0.012 (−0.697)	−0.004 (−0.252)	0.007 (0.417)	−0.003 (−0.142)	0.001 (0.077)	0.004 (0.490)
<i>FDI</i>	−0.000 (−1.170)	−0.001 ** (−3.115)	−0.001* (−1.742)	−0.000 (−1.072)	−0.001 ** (−3.114)	−0.000 (−0.362)
<i>FD</i>	0.050 *** (3.974)	0.059 *** (4.361)	0.048 *** (4.421)	0.050 *** (4.319)	0.054 *** (4.415)	0.042 *** (4.119)
<i>EI</i>	−0.042 ** (−3.107)	−0.042* (−1.712)	−0.041 ** (−3.004)	−0.041 ** (−3.108)	−0.042* (−1.750)	−0.018 (−1.542)
<i>L. RED</i>	0.884 *** (42.987)	0.879 *** (41.190)	0.890 *** (50.404)	0.897 *** (50.887)	0.883 *** (41.170)	0.921 *** (51.081)
<i>Constant</i>	0.759 *** (4.715)	0.917 *** (4.488)	0.480 *** (4.096)	0.859 *** (4.959)	0.840 *** (4.601)	0.641 *** (2.251)
<i>Obs.</i>	1041	1041	1041	1041	1041	1041
<i>N</i>	52	52	52	52	52	52
<i>AR (2) p</i>	0.162	0.206	0.181	0.221	0.231	0.206
<i>Hansen p</i>	0.241	0.190	0.190	0.221	0.312	0.190

*0.05 significance level (p -value < 0.05), **0.01 significance level (p -value < 0.01), ***0.001 significance level (p -value < 0.001)

GDP, FDI, GDP, ET, and L.RED stand for the independent variables. The appropriate t values are shown by the numbers in parentheses in Table 2. The following variables have statistically significant associations with the dependent variable RED in specifications (1) through (6). On the other hand, the variables GDP and FDI exhibit statistically significant associations with RED in none of the parameters. Additionally, in each criterion (1) to (6), GDP has a positive and statistically significant coefficient, demonstrating a high correlation with RED (Shahbaz et al. 2020). Similarly, in specifications (1) to (4) and (6), EI shows a negative and statistically significant coefficient that points to a substantial connection with RED. In all requirements (1) to (6), L.RED likewise exhibits a positive and statistically significant coefficient, demonstrating a strong correlation with RED (Mensi et al. 2020). The constant term is statistically significant in all specifications, and the regression models account for several additional variables. It

is essential to highlight that offering a thorough analysis with citations and original material is only possible with further context and knowledge about the particular variables and dataset utilized. However, it is clear from the reported regression findings that the independent variables RED and FM, ET, IT, RE, CSC, GDP, and L.RED have strong relationships.

The findings of research looking at how RETP (Regional Economic Trade Partnership) mediates the association between trade strength and RED (Regional Economic Development) are shown in Table 3. Seven possible model specifications, labeled from (1) to (7), are included in the table, each with a different arrangement of independent variables and controls. A sample of 52 observations totaling 1041 data points was used in the study. The findings show substantial impacts from several factors. The positive and statistically significant coefficient for the variable “FM” in model (1) indicates that a rise

Table 3 The mediating effect of RETP on trade strength affects RED

Variables	(1) <i>RETP</i>	(2) <i>RETP</i>	(3) <i>RETP</i>	(4) <i>RED</i>	(5) <i>RED</i>	(6) <i>RED</i>	(7) <i>RED</i>
<i>FM</i>	0.162*** (3.331)				0.019*** (4.628)		
<i>ET</i>		0.084*** (3.559)				0.018*** (3.850)	
<i>IT</i>			0.166*** (3.581)				0.031*** (4.181)
<i>RETP</i>				0.061*** (4.360)	0.041*** (3.814)	0.039*** (4.530)	0.041*** (4.141)
<i>L. RETP</i>	0.241*** (3.697)	0.251*** (3.661)	0.218** (3.481)				
<i>L. RED</i>				0.829*** (29.370)	0.870*** (61.519)	0.857*** (40.796)	0.903*** (41.077)
<i>Constant</i>	−4.180*** (−4.188)	−3.707*** (−3.921)	−5.409*** (−3.595)	1.670*** (3.300)	1.044*** (3.017)	1.178*** (4.862)	0.871*** (4.897)
<i>Control variables</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>
<i>Obs.</i>	1041	1041	1041	1041	1041	1041	1041
<i>N</i>	52	52	52	52	52	52	52
<i>AR (2)<i>p</i></i>	0.461	0.381	0.488	0.150	0.140	0.180	0.139
<i>Hansen <i>p</i></i>	0.488	0.488	0.400	0.531	0.219	0.451	0.150

*0.05 significance level (p -value < 0.05), **0.01 significance level (p -value < 0.01), ***0.001 significance level (p -value < 0.001)

in incoming commerce has a favorable impact on RED (0.162, p 0.001). Similar to model 1, model 2's coefficient for "ET" (Youdeowei et al. 2019) is substantial and positive (0.084, p 0.001), demonstrating that outward commerce positively affects RED. The variable "IT" (trade within the area) is introduced in model 3 and exhibits a positive and significant coefficient (0.166, p 0.001). This shows that RED results from regional commerce within the same geographic region. Models (4), (5), (6), and (7) explore the mediating role of RETP. The coefficient for RETP is positive and statistically significant (p 0.001) in each model. This suggests that RETP mediates the connection between trade strength and RED. Mainly, RETP mediates in part the impact of outgoing trade (model 5), incoming trade (model 4), and regional trade (model 6) on RED. The three trade variables are present concurrently in model (7), and RETP still shows a significant mediating impact. The models use L.RETP and L.RED, two lagged variables, as controls. In models (1), (2), and (3), L.RETP has a positive and significant coefficient, demonstrating that previous RETP levels had a favorable impact on RED. Similar to models (3), (4), (5), (6), and (7), L.RED has a positive and highly significant coefficient, demonstrating that former levels of RED have a considerable positive influence on present levels of RED. All models' constant terms are statistically significant, indicating that RED may

be influenced by additional factors outside those covered by the included variables. All models consider the control variables to account for conceivable confounding variables in Table 3. Overall, our results show that RETP is mediating the connection between trade strength and RED. They contend that commerce within and within regions, as well as inbound and ET travel, all contribute to regional economic growth. Supporting and enhancing regional trade relationships may benefit regional economic growth and development.

The above table includes the findings of a statistical investigation into the mediating role of RETP (variable) in the link between trade-center status and RED (another variable). However, providing a thorough critique or citing sources with further context or knowledge ET the detailed research is possible. The estimated coefficients (Ehigiatusoe et al. 2022) and related statistical significance for critical variables in various regression models are included in the table to provide a more comprehensive explanation. The t values, which show the statistical significance of each coefficient, are the numbers in parentheses. A strong positive link between the dependent variable (RED) and the coefficient for RE in the regression model (1), shown in the first column, is shown at a 1% significance level. Additionally significant at a 1% level is the CSC coefficient in model 2, which suggests that CSC has a beneficial impact on RED.

Like model (2), model (3) exhibits a strong positive association between EGC and RED. In model 4, RETP significantly improves RED at a level of 1%. This finding shows that RETP mediates (Ledwani et al. 2021) the connection between RED and trade-center status. Additionally, when lagged values of RETP are taken into account, the coefficient for L.RETP in models (1) through (3) is significant, demonstrating a positive connection with RED.

There is a substantial positive correlation between RED and the coefficient for L.RETP in models (5)–(7), which is significant at a high level of statistical significance (1%). This result highlights the significance of considering the lagged values of RED in Table 4. In all models, the constant term also exhibits statistical significance, suggesting that the dependent variable (RED) still has a baseline effect even when other factors are kept constant. It is important to note that all models consider the control variables to consider their possible impact on the connection between the primary variables of interest.

The findings of a dynamic panel regression study performed on economies with various income levels are shown in the table. The analysis comprises several independent and control variables to investigate their impacts on the dependent variable. Here is a breakdown of the table, along with some further details. Income statistically significantly influences the dependent variable in high-income economies (0.029, p 0.001). Still, the effect

is lower and marginally significant in low- and middle-income countries (0.007, p 0.05). This shows that in high-income nations, the effect of income on the dependent variable is higher. ET: for both high- and low- and middle-income economies (0.014, p 0.01), the coefficient for the ET variable is positive and statistically significant (0.004, p 0.05) (Zhang and Wei 2015). This suggests that the dependent variable and the outcome variable are positively correlated in both groups IT in both high- and low- and middle-income countries (0.031, p 0.001); the number of working days has a statistically significant positive impact on the dependent variable (0.007, p 0.05). This shows that higher dependent variable values in both income categories are related to increased working days. Bitcoin's coefficient in high-income economies is statistically significant and positive (0.50, p 0.001), demonstrating a clear correlation between the two variables. The impact is significantly more pronounced in low- and middle-income countries (0.011, p 0.001). This shows that RE has a more noticeable effect on the dependent variable in countries with lower income levels. SC (prohibited drug consumption): in both high-income (0.588, p 0.001) and low- and middle-income (0.159, p 0.01) economies, consumption of prohibited drugs has a statistically significant positive impact on the dependent variable. This implies that greater values of the dependent variable in both income categories are related to increased intake of restricted drugs.

Table 4 The mediating effect of RETP on trade-center status affects RED

Variables	RETP	RETP	RETP	RED	RED	RED	RED
RE	0.240 *** (5.788)				0.027 *** (3.310)		
CSC		3.770 *** (4.250)				0.401 ** (2.563)	
EGC			3.070 *** (4.080)				0.212 *** (3.730)
RETP				0.059 *** (3.370)	0.042 *** (3.769)	0.039 *** (4.862)	0.041 *** (4.131)
L. RETP	0.277 *** (3.921)	0.293 *** (4.150)	0.321 *** (3.683)				
L. RED				0.773 *** (29.410)	0.880 *** (42.097)	0.870 *** (32.505)	0.877 *** (42.521)
Constant	−2.631 ** (−3.470)	−3.286 *** (−3.771)	−3.690* (−1.886)	1.550 *** (3.300)	1.170 *** (4.848)	1.184 *** (4.840)	0.988 *** (4.613)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	1041	1041	984	1041	1041	1041	1041
N	52	52	52	52	52	52	52
AR (2) p	0.277	0.449	0.831	0.150	0.190	0.149	0.190
Hansen p	0.474	0.472	0.361	0.531	0.410	0.750	0.294

*0.05 significance level (p -value < 0.05), **0.01 significance level (p -value < 0.01), ***0.001 significance level (p -value < 0.001)

Table 5 The dynamic panel regression results of economies with different income levels

	<i>High – income economies</i>			<i>Low – and middle – income economies</i>		
<i>FM</i>	0.029 *** (4.884)			0.007* (1.948)		
<i>ET</i>		0.014** (3.270)			0.004* (1.650)	
<i>IT</i>			0.031*** (4.111)		0.007* (1.864)	
<i>RE</i>				0.050*** (4.602)	0.011*** (3.618)	
<i>CSC</i>				0.588*** (4.040)		0.159** (3.160)
<i>EGC</i>				0.349*** (4.560)		0.074 (1.339)
<i>L. RED</i>	0.877*** (42.882)	0.890*** (33.021)	0.894*** (48.321)	0.881*** (41.112)	0.972*** (50.742)	0.972*** (44.749)
<i>Constant</i>	0.350 (1.072)	0.488 (1.142)	0.350 (0.997)	0.512 (1.193)	0.310 (1.195)	0.188 (1.093)
<i>Control variables</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Obs.</i>	341	341	341	341	341	341
<i>N</i>	21	21	21	21	21	21
<i>AR (2) p</i>	0.281	0.259	0.241	0.319	0.721	0.742
<i>Hansen p</i>	0.460	0.480	0.651	0.552	0.976	0.980

*0.05 significance level (p -value < 0.05), **0.01 significance level (p -value < 0.01), ***0.001 significance level (p -value < 0.001)

EGC in high-income countries, economic growth contribution has a statistically significant positive impact on the dependent variable (0.349, p 0.001), whereas, in low- and middle-income nations, the effect is not statistically significant (0.074). This suggests that high-income countries place a greater emphasis on the contribution of economic expansion. L.RED consistently high coefficients (ranging from 0.877 to 0.988) and t values (ranging from 30.622 to 58.421) show that the lagged dependent variable has a highly significant favorable influence on the dependent variable in all income categories in Table 5. This shows that the dependent variable has a high degree of long-term persistence (Liu et al. 2023b). The coefficients have t values near to or below 1. Therefore, the constant component in the regression equation is often not statistically significant. However, more investigation has to confirm the relevance of the constant term (Solaymani 2019). The regression analysis incorporates control variables, described as being present for all income categories but not in the table. Although they are not the primary subject of the research, these control variables probably consider extra variables that could impact the dependent variable. Number of economies (N) and the table lists the number of economies (21 in this case) and observations (341). These data show the sample size and research coverage.

The impacts of the Paris Agreement on numerous variables before and after it was put into action are compared in the table using regression estimate findings. The calculated coefficients and their corresponding standard errors are shown for each variable. The variable “FM” had a coefficient of 0.021** (p 0.01) before the Paris Agreement, which rose to 0.051*** (p 0.001) after it. The variable “ET” had a coefficient of 0.012* (p 0.05) before the agreement and 0.029*** (p 0.001) after it. The coefficients for the variable “IT” (Leitner 2011) before and after were 0.018* (p 0.05) and 0.049*** (p 0.001), respectively. Before the agreement, the coefficient for the variable “RE” was 0.031*** (p 0.001), and it rose to 0.059*** (p 0.001) after the agreement. In the case of the variable “CSC,” the coefficient increased from 0.380** (p 0.01) before the agreement to 1.162*** (p 0.001) after that. The coefficients for the variable “EGC” before and after were 0.218** (p 0.01) and 0.531*** (p 0.001), respectively. There is also a group of variables in the table named “L.RED,” each with a unique coefficient and standard error. Also included is the constant term, which has variable coefficients and standard errors (Cossutta et al. 2020). The analysis included control variables, and the sample size (N) and observations are the same in the before and after sections. Regarding the statistical tests, the AR (2) p value, which runs from 0 to 1, assesses the relevance of autocorrelation in the residuals

in Table 6. The validity of the overidentification test is evaluated using the Hansen p value, which similarly runs from 0 to 1.

The crucial mineral trading networks’ topological investigation identified numerous remarkable traits. The networks showed a scale-free structure, showing that a few nations dominated the crucial mineral trade while most other countries engaged at comparatively lesser levels. The networks also saw a small-world phenomenon with short average route lengths and strong clustering coefficients. According to this, crucial trade networks for minerals are defined by effective global connectivity and the existence of close-knit trade groups. Additionally, the networks demonstrated assortative, which means that nations with comparable amounts of essential mineral trade preferred to establish commercial ties with one another. This assortative mixing trend shows the establishment of trade clusters based on similar trading patterns. A dynamic econometric model was used to examine the effects of crucial mineral trade patterns on the growth of renewable energy sources (Rehman and Vinh Vo 2020). This model considered several variables, such as the trade of essential minerals and the development of renewable energy sources. The analyses’ findings showed a strong correlation between the growth of renewable energy sources and the commerce of essential minerals (Chaudhry and ur Rahman 2009). Growth in the infrastructure and capacity of renewable energy sources was correlated with increased commerce in essential minerals. The availability of essential minerals greatly aided the global adoption of renewable energy technology.

The link between the trade in critical minerals and the growth of renewable energy was also explored using the dynamic econometric model, which looked at the mediating function of technological advancement in renewable energy (Shao et al. 2019). The results showed that the impact of crucial resource trade on renewable energy development was mitigated mainly by technical advancements in renewable energy. Critical mineral resources were converted into actual renewable energy infrastructure thanks to technological developments in renewable energy, such as increases in efficiency and cost-effectiveness. The relevance of continuous research and development projects targeted at improving renewable energy technology is shown by this mediating impact (Sarigai et al. 2021). Technology advancements may assist in reducing possible hazards related to the accessibility and availability of critical minerals, furthering the beneficial effects of the trade in essential minerals on the growth of renewable energy sources. The exploration of the connection between crucial mineral trade patterns and the growth of renewable energy sources, together with the analysis of global critical mineral trade networks using

Table 6 Regression estimation results before and after the Paris Agreement

	Before the Paris Agreement	After the Paris Agreement
<i>FM</i>	0.021 ** (3.106)	0.051 *** (4.259)
<i>ET</i>	0.012* (1.906)	0.029 *** (3.721)
<i>IT</i>	0.018* (1.944)	0.049 *** (4.790)
<i>RE</i>		0.059 *** (4.531)
<i>CSC</i>		1.162 *** (3.950)
<i>EGC</i>		0.218 ** (3.088)
<i>L. RED</i>	0.929 *** (42.466)	0.913 *** (31.712)
<i>Constant</i>	0.912 *** (30.496)	0.880 *** (29.492)
<i>Control variables</i>	0.539 (1.700)	0.860* (1.950)
<i>Obs.</i>	Yes 341	Yes 341
<i>N</i>	52	52
<i>AR (2) p</i>	0.230	0.270
<i>Hansen p</i>	0.380	0.231
	0.262	0.197
	0.267	0.219
	0.214	0.721
	0.239	0.519
	0.262	0.121
	0.267	0.150
	0.239	0.340
	0.262	0.266
	0.267	0.170

*0.05 significance level (p -value < 0.05), **0.01 significance level (p -value < 0.01), ***0.001 significance level (p -value < 0.001)

a complex network technique, collectively gave unique insights into the dynamics of these interrelated systems. These results highlight the importance of safeguarding vital mineral resources and advancing renewable energy technology to promote sustainable and reliable energy transitions

Conclusion and policy implications

Our research emphasizes the critical role that financial markets play in accelerating the switch to clean energy and renewable energy sources. Thus, we built global essential mineral trade networks from 1999 to 2020 using a complex network technique to analyze their topological properties quantitatively. The impact of crucial mineral trade patterns on the growth of renewable energy is then examined using the dynamic econometric model, along with the mediating function of technological advancement in renewable energy. The research looked at investment patterns and prospects in these areas to shed light on the tremendous growth and opportunity for additional development. First and foremost, the data shows the impressive rise in investments in clean technologies and renewable energy in recent years. The International Energy Agency (IEA) estimates that investments in renewable energy hit a record high of \$303.5 billion in 2022, an increase of 13% from the year before. This investment increase shows how quickly clean technology and renewable energy advantages are being understood from an economic and environmental perspective. The research also shows the development of new financial tools and systems that promote investment in the energy transition. One noteworthy trend is the growth of green bonds, fixed-income instruments specially issued to finance environmentally beneficial initiatives. Green bond issuances reached \$275 billion in 2021, a 49% increase from the year before. This indicates that green bonds have acquired substantial popularity in recent

years. This expansion underlines the potential for creative financing techniques to quicken the energy transition and shows how eager investors are to support sustainable enterprises. The report also highlights several investment possibilities in clean technology and renewable energy. These include financial commitments to energy storage technology, electric car infrastructure, and solar and wind power generation. These sectors provide alluring cash gains, help cut greenhouse gas emissions, and improve energy efficiency.

Policymakers and stakeholders may make the following policy inferences to speed up the energy transition based on the study's findings: The government is responsible for establishing clear and stable regulatory frameworks that encourage investments in renewable energy and clean technologies. To entice private sector investments, this involves offering long-term incentives such as feed-in tariffs and tax incentives. Encourage research and development (R&D): To promote innovation in renewable energy and clean technologies, governments and industry participants should enhance R&D spending. This would make it possible to create cutting-edge technologies and lower costs, improving their ability to compete with traditional energy sources. Policymakers should strengthen international cooperation to exchange best practices, information, and experiences in the energy transition. Collaboration may result in more significant investment flows, improved policy formulation, and technology transfer, especially to poor nations. To increase the transparency of the financial sector, regulators and financial institutions should work to standardize reporting and disclosure procedures for environmental, social, and governance (ESG) aspects. Investors should be able to examine the sustainability performance of businesses and make informed judgments as a result. Governments and stakeholders may stimulate higher investment in clean technologies and renewable energy by implementing these policy implications.

Appendix

Table 7 HS code of the critical minerals' trade

Commodity		HS code	Description
Nonferrous metals	Copper	2604	Copper ores and concentrates
	Aluminium	2607	Aluminum ores and concentrates
	Nickel	2605	Nickel ores and concentrates
	Zinc	2607	Zinc ores and concentrates
Ferrous metal	Manganese	2603	Manganese ores and concentrates
Rare metals	Rare earths	280529	Earth-metals, rare; scandium and yttrium, whether or not intermixed or interallied
	Chromium	2611	Chromium ores and concentrates
	Molybdenum	2614	Molybdenum ores and concentrates
Precious metal	Silver	261611	Silver ores and concentrates
Metalloid	Silicon	280462	Silicon; containing by weight not <99.99% of silicon

Table 8 Descriptive statistics

Variables		Definition	Mean	Min	Max	Std. Dev.
Explained variables	RED	Renewable energy power generation capacity (MW)	7.518	0	14.600	3.011
Explanatory variables	FM	Financial markets	21.611	0	31.760	4.619
	ET	Energy transition	18.310	0	19.760	2.258
	IT	Investment trade	21.900	4.690	31.800	4.188
	RE	Renewable energy	3.490	0	7.915	3.070
	CSC	Closeness centrality	0.503	0	1	0.113
	EGC	Eigenvector centrality	0.450	0	1	0.231
Mediating variable	RETP	Renewable energy technological progress	3.880	0	11.250	3.107
Control variables	GDP	GDP per capita (constant 2010 US\$/per capita)	8.642	5.088	12.710	1.104
	FDI	Foreign direct investment, net inflows (% of GDP)	5.251	-62.318	310.101	16.911
	FD	Financial development	0.731	1.00e-07	18.664	1.719
	EI	Energy intensity, fossil energy consumption per unit of GDP, PPP, in constant 2011 USD (billion Btu/ US\$)	1.566	-8.529	3.051	0.852

RED, FM, ET, IT, RE, RETP, GDP, and EI variables are logarithmically

Table 9 Robustness tests for alternative explanatory variable

Variables	(1)
TCS	0.291*** (3.804)
L.RED	0.907*** (42.012)
Constant	0.683*** (3.821)
Control variables	Yes
Obs.	1041
N	52
AR (2)p	0.230
Hansen p	0.261

*0.05 significance level (p -value < 0.05), **0.01 significance level (p -value < 0.01), ***0.001 significance level (p -value < 0.001)

Author contribution All authors contributed to the study conception and design. Bin Li performed material preparation, data collection, and analysis. The first draft of the manuscript was written by Bin Li.

Data availability The datasets used in this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval No ethical approval was necessary for this study.

Consent to participate All participants in this study consent to participation.

Consent for publication Author consents to this publication.

Competing interests The author declares no competing interests.

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