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The transition from exhaustible to renewable resources: Investigating the dynamic effect of natural resources and monetary liquidity on consumption of renewable energy

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ABSTRACT

The global shift towards renewable energy is central to climate change mitigation, yet adoption remains uneven, particularly in resource-rich economies where financial liquidity constraints and fossil fuel dependence persist. This study advances the literature by providing a novel integrated analysis of how financial liquidity, digitalisation, and institutional quality jointly shape renewable energy adoption in both resource-abundant and resource-scarce economies. Using a dynamic panel data model, the research examines interactions among financial depth, digital advancements, and institutional quality in 124 economies, showing that good governance and financial policies can convert resource wealth into renewable energy drivers. Results indicate that broad money significantly predicts renewable energy usage, dependent on regulatory frameworks that encourage green investments. The traditional resource curse hypothesis is challenged, demonstrating that strong regulations can utilise natural wealth for sustainable energy transitions. This study contributes new evidence to the renewable energy–finance nexus and suggests that policymakers should focus on financial instruments supporting green initiatives, enhancing digital infrastructure, and enforcing solid governance. Resource-rich countries can maximise their energy potential by aligning monetary policies with sustainability objectives, fostering a cleaner and more sustainable future.

1. Introduction

The global transition to renewable energy and sustainable governance of natural resources faces growing complexities in the digital age, while renewable energy adoption is recognised as essential for reducing reliance on finite natural resources and mitigating environmental degradation. Financial and technological factors significantly influence the pace and effectiveness of this transition (Horky & Fidrmuc, 2024; Usman & Balsalobre-Lorente, 2022). Despite their advanced infrastructure and financial resources, developed countries face significant challenges in renewable energy consumption. A substantial factor is the intermittency of renewable energy sources, which creates difficulties in ensuring a stable energy supply. Integrating an excessive share of renewable energy into the existing energy systems requires substantial investment in energy storage solutions and modernisation, even with advanced grid systems (IRENA, 2019; Yadav et al., 2024; Yang & Long, 2024). In contrast, developing countries often face more severe challenges in renewable energy consumption. Lack of financial resources and investment in green energy is a major issue. Developing nations usually depend on international aid and private investment to fund renewable energy infrastructure, creating a reliance on external finances that may not always be sustainable (Jie et al., 2024; Xu et al., 2024).

Financial flows can drive funding for renewable energy infrastructure, but market dynamics and institutional structures often shape their allocation. Similarly, digital technology adoption is reshaping energy systems and resource management practices (Sadorsky, 2011). The entrenched interests of fossil fuel industries often influence energy policies, slowing the pace of the transition, although developed economies lead in renewable energy technologies, transitioning completely from fossil fuels remains slow due to existing energy infrastructure and market dynamics (IEA, 2019). Lack of technological expertise required to deploy and maintain renewable energy systems is a critical barrier in developing countries, which often lack access to the latest technologies and restrict countries' ability to implement large-scale renewable energy projects (Bhattacharyya & Palit, 2016). Moreover, institutional weaknesses, such as corruption and poor governance, can further impede renewable energy adoption by misallocating resources and undermining long-term planning (Vatamanu & Zugravu, 2023). Energy access disparities exacerbate the problem; many rural areas in developing countries remain off-grid, making it challenging to deliver renewable energy where it is needed most. While decentralised renewable energy systems such as solar microgrids have proven effective in extending energy access, these solutions require substantial financial and policy support, often lacking (World Bank, 2020; IMF, 2020). Additionally, reliance on traditional biomass energy sources persists in many low-income regions, posing significant health and environmental risks.

Energy Transition Theory (ETT) underscores the importance of financial mechanisms in enabling innovation and infrastructure development required for renewable energy adoption (Sovacool et al., 2020). Increased liquidity in the financial system can facilitate access to credit, reduce borrowing costs, and encourage investment in renewable energy technologies (Gibbs, 2000). Higher availability of financial flows can stimulate funding for wind, solar, and hydroelectric projects, thereby accelerating the transition away from fossil fuels. The contribution of government and policy framework posited in shaping the effect of financial systems like broad money on the energy transition, and policies that regulate financial flows may amplify the positive effects of broad money by directing investments toward renewable energy projects (Sovacool & Geels, 2016). ETT accentuates the need for strategic investments and policy interventions to ensure that increased financial liquidity translates into tangible benefits for renewable energy development and natural resource conservation. Ecological Modernisation Theory (EMT) complements ETT by emphasising the institutional and financial dimensions of environmental change, positing that economic growth and environmental protection can be jointly reinforcing through the support of technological adoption and effective policies (Dauda, 2019; Jänicke, 2008; Mol & Sonnenfeld, 2000; York & Rosa, 2003). This study incorporates EMT to investigate how financial flows and the adoption of digital technology influence the allocation of financial liquidity towards the handling of natural resources and the consumption of renewable energy. However, prior studies focused separately on the technological or financial aspects; this study merges these dimensions to come up with a more nuanced analysis.

In advanced economies, the renewable energy transition is primarily constrained by system-level challenges, including the scaling of mature technologies, their integration into legacy energy grids, and persistent market inertia favouring established fossil fuel industries. Despite ample financial capacity, capital allocation remains skewed towards carbon-intensive sectors, delaying the reorientation of energy portfolios. In addition, the inherent intermittency of renewable sources necessitates substantial investments in grid flexibility, energy storage, and transmission upgrades to preserve system reliability and energy security (Dauda, 2019). By contrast, the constraints faced by developing economies are more structural and binding, reflecting chronic financial scarcity, fragile infrastructure, and limited institutional capacity. Many of these countries rely heavily on natural resource rents as a core driver of economic growth, a dependence that frequently reinforces extractive development paths and environmentally unsustainable practices. Weak and shallow financial systems further impede the mobilisation of domestic liquidity into renewable energy investments, locking energy systems into traditional and often polluting sources such as coal and biomass (Bhattacharyya & Palit, 2016). These challenges are compounded by deficits in technological capability and skilled labour, which undermine both the deployment and long-term operation of renewable energy systems, particularly in rural and off-grid settings (IMF, 2020). Addressing these intertwined constraints requires not only innovative financing instruments but also a strategic reconfiguration of how natural resource wealth is governed and channelled. While developed economies must prioritise the redirection of financial flows towards grid modernisation and low-carbon technologies, developing and resource-dependent economies face the more pressing task of transforming natural resource rents and financial liquidity into catalysts for renewable energy adoption. Doing so offers a pathway to break persistent energy-development lock-ins, reduce reliance on non-renewable resources, and stimulate sustainable technological upgrading.

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The research makes a remarkable addition to the corpus of current knowledge in three strands. First, while previous studies have looked closely at the determinants of renewable energy adoption, few have explicitly centred on the interplay between monetary liquidity and natural resource wealth as pivotal factors influencing renewable energy consumption. By integrating these dimensions, this study offers a novel framework for insight into financial and resource-related barriers to sustainable energy transitions. Second, exploration of broad money as a substitute for monetary fluidity and its role in renewable energy consumption. The inquiry identifies the potential of financial systems to mobilise resources toward renewable energy investments, thereby addressing a significant disparity in the literature. While previous research has highlighted the importance of fiscal development in advancing renewable energy adoption (Sadorsky, 2011), this study extends the discourse by explicitly examining how broad money flows can be directed to overcome financial barriers in energy transitions. This intuition is particularly valuable for policymakers and financial institutions seeking to design targeted financial tools such as green bonds and sustainable investment funds. Third, the utilisation of natural resource wealth to finance renewable energy initiatives. Resource-rich economies, particularly in developing regions, often face the paradox of resource abundance and low renewable energy adoption due to overdependence on non-renewable resources. This study provides empirical evidence on how resource wealth can be channelled into renewable energy usage, offering a pathway to sustainable development. Examining how financial flows interact with digital technology dimensions reveals synergies or conflicts in their combined impact on renewable energy and natural resources. The availability of fiscal depth may accelerate the adoption of resource-efficient technologies, which might lead to resource-intensive technological investments.

2. Literature Review

2.1. Theoretical Framework

Ecological Modernisation Theory (EMT), developed by Huber (1985) and Jänicke (2008), is a prominent framework that examines how societies can harmonise economic growth and environmental sustainability through technological, institutional, and societal innovations. The theory posits that ecological challenges may be addressed within the existing political and economic structures, provided that the structures are reoriented towards sustainability. EMT shifts the environmental discourse from focusing on limiting growth to emphasizing modernizing and greening industrial systems. At its core, EMT asserts that economic and environmental goals are not inherently conflicting but can be mutually reinforcing. The perspective challenges traditional views that link economic development to ecological degradation. However, EMTs propose environmental protection to stimulate economic innovation and generate employment opportunities, particularly in sectors that include renewable energy and green technology (Mol & Spaargaren, 2000). Gibbs (2000) argues that adoption and progress in technology play a central role in EMT, significantly reducing environmental harm by improving efficiency, reducing waste, and creating cleaner production methods. The widespread adoption of renewable energy technologies demonstrates how technological progress can mitigate reliance on fossil fuels while fostering sustainable economic development. However, these advancements require adequate financial and policy support to succeed.

A robust framework provided by Energy Transition Theory (ETT) on examining the impact of financial depth and liquidity within an economy on the correlation between resources and consumption of renewable energy. The study on systemic changes rooted within energy systems and theory explores the progression from conventional, fossil fuel-based energy to sustainable, renewable energy-driven systems (Geels, 2002; Sovacool, 2016). ETT offers insights into how financial flows might hinder or catalyse progress toward a sustainable energy future and emphasises the necessity of adopting technology, economic, and societal shifts to achieve a reduction in environmental externalities and dependency on finite natural resources. Moreover, ETT posits that the progression to renewable energy systems is a lengthy procedure that involves technological innovation, institutional change, and behavioural adaptation (Markard et al., 2012). Financial flows support economic transitions and act as a financial enabler that bridges the gap between technological advancements and practical implementation. The link between renewable energy consumption and natural resources is particularly pertinent in the milieu of energy transition, decreasing reliance on fossil fuels. Renewable energy adoption alleviates the strain on finite natural resources while mitigating environmental degradation. However, ETT acknowledges the expansion of renewable energy that involves trade-offs, such as land use for solar farms or resource extraction for battery technologies (Geels, 2014). The role of financial flow becomes critical, as financial policies and investments must be strategically directed to minimise these trade-offs and ensure a just and sustainable transition.

The integration of ETT and EMT supplies a comprehensive scheme for investigating the repercussions of extensive financial flows on the correlation between renewable energy consumption and natural resources. Theories complement one another by addressing both the systemic and institutional aspects of the shift towards sustainable energy systems. However, ETT focuses on the involvement of the dynamic processes and technological advancements in transitioning energy systems, while EMT emphasises the role of financial mechanisms and governance in promoting environmental sustainability (Jänicke, 2008; Mol & Sonnenfeld, 2000; York & Rosa, 2003). The integration provides a robust rationale for examining the coordination of financial, technological, and institutional factors in the relationship between natural resources and renewable. It allows this study to bridge the gap between macroeconomic indicators, such as financial flows, and their environmental implications, providing a comprehensive understanding of how financial systems can contribute to sustainable development (Usman & Balsalobre-Lorente, 2022). The long-term transition dynamics and the role of technological innovation are explained with a rationale that focuses on the economic and policy mechanisms that facilitate these transitions.

2.2. Relationship between natural resources and consumption of renewable energy

The correlation between natural resources and consumption of renewable energy seemed to be a focal point of empirical research, given the pressing need for sustainable development and environmental preservation (Al-Mulali & Ozturk, 2015; Fridgen et al., 2021; Payne, 2010; Sadorsky, 2009). Renewable energy consumption is widely regarded as a critical pathway to reducing dependence on finite natural resources and mitigating environmental deterioration. Several studies highlight the role of renewable energy in conserving natural resources by reducing dependency on non-renewable energy and reducing the environmental effects of energy production. Yang & Long (2024) argued that increased adoption of renewable energy sources significantly reduces environmental externalities that are often linked to the overexploitation of natural resources, concluding the prospective of renewable energy to act as a substitute for non-renewable resources, hence alleviating environmental pressures. However, Han et al (2023) conducted a panel data analysis on 162 developed and developing economies between 1990 and 2021 and concluded that consumption of renewable energy retains a positive association with natural resource sustainability by limiting the extraction and consumption of finite resources, promoting greening economic recovery.

Moreover, the stream of literature investigates the spatial and contextual proportions of the renewable energy and natural resources nexus. A cross-country study, Han et al (2023) disclose that the impact of consuming renewable energy on natural resource conservation varies depending on a nation's income, energy policies, and resource endowments. High-income countries with advanced energy policies revealed a stronger relationship linking renewable energy adoption and resource sustainability. Conversely, in low-income countries, the lack of technological and financial capacity to transition to renewables limited the potential benefits. Wang et al (2024) analysed panel data from 30 countries and demonstrated that countries with stronger governance structures were more successful in leveraging renewable energy to conserve natural resources. Emphasised that effective regulatory frameworks and transparent policies enhance the constructive repercussions of natural resources on renewable energy consumption by ensuring sustainable practices throughout the energy supply chain.

2.3. Impact of financial depth and adoption of digital technology

The global alteration to renewable energy and justifiable management of natural resources faces growing complexities during the digital age. Recognising the importance of reducing reliance on finite natural resources and mitigating environmental degradation, financial and technological development significantly influence the pace and effectiveness of this transition. Essential for economic growth may not always flow into sustainable sectors without appropriate policy interventions, potentially exacerbating resource exploitation (Usman & Balsalobre-Lorente, 2022; Vatamanu & Zugravu, 2023). Xu et al (2024) employed the non-parametric procedure on the moment of quantile regression (MMQR) and parametric methods, including dynamic and fully modified ordinary least squares (DOLS and FMOLS) in high-growth nations between 1989 and 2021 to examine how natural resources rents, financial, and economic expansion are intertwined. The results show a curse of natural resources covering all quantiles, whereas economic expansion enhances financial development; however, the production of renewable power hurts financial development in high-growth nations. Wei & Nie (2024) explore the capacity of renewable energy, natural resources, and carbon dioxide emissions by employing the autoregressive distributed lag (ARDL) estimator, DOLS, and FMOLS between 1980 and 2021. The research found the dual appurtenances of natural resources and renewable energy on ecological integrity, while fossil fuel consumption and economic growth significantly worsen ecological degradation. However, the Granger causality test validated the conclusion of the effect of financial progressions and renewable energy on carbon emissions.

Yadav et al (2024) performed a panel analysis on BRICS to investigate the correlation between financial enlargement and the use of renewable energy. The study revealed that economic progress and domestic credit are related to increased adoption of renewable energy. Again, digital technology adoption reshapes energy systems and resource management practices, despite their promise to enhance energy effectiveness and lessen resource severity, is resource-intensive itself, requiring significant amounts of critical materials such as rare earth metals and cobalt (IRENA, 2019). The dynamics of digital technology on financial flows create a complex nexus that may either support or hinder the sustainable management of natural resources through renewable energy adoption. Li et al (2024) retain a dynamic ARDL procedure to explore the effect of China’s natural resources, fintech, trade, and energy consumption on economic advancement from 1981 to 2023. The study disseminates the existence of an integrated positive influence of exports and imports, fintech, and usage of renewable energy on the GDP across different frequencies and time intervals. Fintech played a significant part in transforming China’s finances with the widespread adoption of efficient and convenient mobile payments. Kumar (2024) assessed the consequences of digitalisation and natural resources on India’s economic progress between 1970 and 2020 and found the notable core of integrating digital technology with sectors of the economy, such as financial development, to encourage market openness.

The findings of this research have significant suggestions for policymakers and offer evidence-based recommendations on how financial systems can be aligned with sustainable development goals, ensuring that financial flows into renewable energy and resource-efficient technologies. The dual role of digital technologies, advocating for resource-conscious innovation in their development and deployment, by integrating financial and technological perspectives, the study will contribute to a holistic understanding of the renewable energy-natural resource nexus, addressing critical disparities in existing literature. The study confers the current corpus of knowledge in three strands. First, while prior studies have explored the contribution of fiscal policy in adopting renewable energy, the specific influence of monetary liquidity remains underexplored. The liquidity available within an economy may fund renewable energy projects or drive resource-intensive growth. By investigating the impact of broad money on the consumption of renewable energy and natural resources, the study will extend discernment into whether monetary depth supports sustainable transitions or perpetuates resource exploitation. Second, this study will investigate how digital technology adoption mediates the link between consuming renewable energy and natural resources, offering a nuanced perspective on its benefits and trade-offs.

3. Method

3.1. Data and variable description

We obtained data from the International Energy Agency (IEA) which supplies detailed data on energy consumption, including renewable energy usage; International Monetary Fund (IMF) Financial Statistics contains data on financial development, liquidity, and macroeconomic stability indicators; International Telecommunication Union (ITU) provides insights into the penetration and usage of digital technology; and World Bank Development Indicators (WDI) provides data on economic indicators. Table 1 presents the variable description and expected sign. Renewable energy consumption is considered a dependent variable abstracted from the IEA, broad money as a percentage of GDP, proxying financial liquidity, reflects the overall availability of funds in an economy, which influences financial flows and credit availability. Broad money, as a key indicator of financial depth and liquidity within an economy, significantly influences the allocation of capital toward renewable energy projects. The percentage of natural resource rents used as a proxy for natural resource wealth measures the share of GDP derived from resource extraction, reflecting the short-term economic contribution of natural resources. Digital technology includes internet penetration and usage, fixed and mobile phone subscriptions per 100 people, abstracted from the ITU. We included control variables abstracted from WDI, and the selection of control variables is based on economic theory and prior empirical literature. Economic growth and governance are included as they significantly influence renewable energy consumption and financial flows. Ensuring consistent and comparable data across countries for all variables, the time selected for this study spans between 2002 and 2021. The selected period captures key policy shifts, technological advancements, and financial crises that have influenced renewable energy adoption

Table 1. Operational Definitions

Variable	Description	Measurement	Expected sign	Source
rec	Consumption of renewable energy	Percentage (%) of total energy consumption	NA	IEA
broad	Financial flow/liquidity	Percentage of broad money as a share of GDP	+/-	IMF
digital	Digital technology	Internet penetration rate, fixed telephone (fts), mobile subscriptions (mbs) per 100 people	-	ITU
natural	Natural resource wealth	Percentage of total natural resource rents as a share of GDP	+/-	WDI
gdp	Per capita GDP growth	The percentage of the annual growth rate of GDP per capita	+/-	
regulatory	Regulatory quality	Includes estimates of the quality of institutions	+/-	

Source: multiple sources

3.2. Methodology

This research employs dynamic panel data models to examine the impact of monetary liquidity and natural resource dependence on renewable energy consumption. The empirical results offer policy-relevant insights into how financial and technological channels can be leveraged to promote sustainable energy adoption. Given the presence of potential endogeneity, serial correlation, and dynamic persistence in renewable energy consumption, the endogenous variable is modelled as a lagged dependent variable within the dynamic specification. Moreover, the study applies the generalised method of moments (GMM) estimators developed by Arellano & Bond (1991), Arellano & Bover (1995), and Blundell & Bond (1998), which are well suited to addressing dynamic relationships by controlling for unobserved heterogeneity, simultaneity bias, and measurement errors. The baseline dynamic panel model is described as follows:

$$rec_{it} = \alpha rec_{it-1} + \beta_1 broad_{it} + \beta_2 natural_{it} + \sum_{k=1}^{p} \beta_k X_{itk} + \eta_i + \varepsilon_{it} \quad (1)$$

Where rec_{it} and rec_{it-1} respectively denoted as renewable energy consumption for the country i at time t and lagged dependent variable, $broad$ denoted financial liquidity, proxied by broad money, while $natural$ signifies natural resources wealth, whereas X_{itk} includes a vector of modulated variables such as economic growth, governance, and digital technology adoption, including internet users, fixed telephones, and mobile phone subscriptions. η_i captures discarded country-specific impacts and ε_{it} is the idiosyncratic error term. Arellano & Bond (1991) propose the first-differenced GMM estimator to exclude country-specific effects and appropriate lagged estimates of rec_{it} are used as instruments to address the endogeneity of rec_{it-1}. The model becomes:

$$\Delta rec_{it} = \alpha \Delta rec_{it-1} + \beta_1 \Delta broad_{it} + \beta_2 \Delta natural_{it} + \sum_{k=1}^{p} \beta_k \Delta X_{itk} + \Delta\varepsilon_{it} \quad (2)$$

The difference GMM estimator may deteriorate from feeble instruments if the variables exhibit high persistence. Arellano & Bover (1995) extend the methodology by introducing the system GMM estimator, which integrates the differenced with the level equation. This approach improves efficiency by using additional moment conditions $\mathrm{E}(\eta_i + \varepsilon_{it}|Z_{it}) = 0$, where Z_{it} represents the set of valid instruments. Moreover, Blundell & Bond (1998) refine the system GMM estimator by incorporating ancillary moment constraints to enhance the robustness of the estimates. The approach is effective when explanatory variables are highly persistent over time. To ensure the reliability of our estimates, the Arellano-Bond test for autocorrelations was conducted to check for second-order autocorrelation in first-differenced errors, the Hansen and Sargan tests for overidentifying restrictions to validate the validity of instrumental variables, and the Difference-in-Hansen test to confirm the cogency of ancillary instruments in system GMM.

3.3. Estimation Technique

Before estimating the dynamic panel data, it is essential to conduct preliminary tests to corroborate the validity of the results. Panel data regularly reveal the presence of cross-sectional dependence (CSD) due to global shocks or interdependencies among countries. To account for this, we employ Pesaran's (2004) and Pesaran (2015) CSD test, which examines whether residuals across the regional units are correlated, rejects the null hypothesis stipulating the presence of CSD, requiring further adjustments in estimation techniques. The test statistic is computed as follows:

$$CSD = \sum\sum \frac{2}{N(N-1)} \hat{\rho}_{ij} \quad (3)$$

Where $\hat{\rho}_{ij}$ denotes the pairwise correlation of residuals between countries. We utilise a cross-sectional exponential approach, developed by Bailey et al (2016) and Bailey et al (2019) to measure the degree of CSD in panel data, the alpha (α) method helps determine whether the CSD is weak or strong by estimating the exponent from the decay rate of eigenvalues in the covariance matrix. If $\alpha <$ 0.5 dependence is weak, whereas if $\alpha \geq 0.5$ implies the presence of a strong dependence. First- and second-generation panel unit root tests are employed to ensure stationarity of the covariates and appropriate transformations, such as first-differencing performed before model estimation if covariates are established to be non-stationary. We apply the Levin et al (2002), Im et al (2003), and Breitung (2000) as first-generational panel unit root tests, which presume cross-sectional independence. However, given the presence of CSD, second-generation tests such as Pesaran's (2021) Cross-sectionally augmented Dickey-Fuller and IPS (CADF/CIPS) tests are applied to account for cross-sectional interdependencies.

$$\text{Group} - \text{mean tests: } G_t = \frac{1}{N}\sum_{i=1}^{N} \frac{\hat{E}_i}{SE(\hat{E}_i)} \text{ and } G_a = \frac{1}{N}\sum_{i=1}^{N} \frac{T\hat{E}_i}{SE(\widehat{T E}_i)} \quad (4)$$

Panel tests: $P_t = \frac{\sum_{i=1}^{N} \hat{E}_i}{SE(\sum_{i=1}^{N} \hat{E}_i)}$ and $P_a = \frac{\sum_{i=1}^{N} T\hat{E}_i}{SE(\sum_{i=1}^{N} T\hat{E}_i)}$ (5)

We then examine the long-run association between the variables. Westerlund (2007) cointegration test utilised allows for heterogeneity across cross-sections and considers both error correction and panel-specific short-run dynamics. When the null hypothesis of no cointegration is rejected, implies the existence of a stable long-run equilibrium link between the variables, which is crucial for ensuring meaningful economic interpretations of estimated coefficients. The approach consists of four test statistics for group-mean and panel tests, which determine whether the error correction term significantly deviates from zero. Where $\hat{E}_i$ is the estimated error correction term for cross-section i and $SE(.)$ denoted standard error. The test statistics are given an equation (4) and (5).

4. Results and Discussion

4.1. Cross-sectional dependence and exponent

Before model estimation, we employ panel data preliminary estimations such as cross-sectional dependence (CSD), which may occur when residuals across different cross-sectional units are correlated. Ignoring the dependence across variables can lead to biased estimators, ineffective standard errors, and incorrect statistical deductions (Pesaran, 2004; Pesaran, 2015). Renewable energy adoption, financial liquidity, natural resources, and digital technology are often influenced by global policies and economic trends, leading to interdependencies among countries. Table 2, column 2 presents CSD results for all variables; all variables significantly discard the null proposition of no CSD, indicating the presence of CSD. Results imply that it is highly likely that financial markets and liquidity conditions are interconnected globally, whereas renewable energy policies and energy prices are influenced by global climate agreements and economic conditions.

Table 2. CSD, exponent, and first-generation panel unit root tests

Variables	CSD	Alpha	LLC Level
rec	20.515***	0.8915	-6.1617***
broad	187.090***	0.9621	-3.5293***
natural	80.698***	0.8227	-6.8128***
fts	73.940***	0.8937	-10.1136***
mbs	320.287***	1.0000	-9.0641***
internet	332.308***	0.9995	-4.1665***
regulatory	3.498***	0.4473	-16.7345***
gdp	134.350***	0.9562	-5.9466***

Unit Root Test for IPS and Breitung

Variables	CSD	Alpha	IPS Level	IPS First difference	Breitung Level	Breitung First difference
rec	20.515***	0.8915	0.3254	-16.3341***	7.3625	-18.1426***
broad	187.090***	0.9621	0.8449	-14.2850***	9.8195	-22.0186***
natural	80.698***	0.8227	-3.7923***		-10.4142***	
fts	73.940***	0.8937	0.6000	-11.3812***	7.6746	-15.6901***
mbs	320.287***	1.0000	0.884	-10.9374***	15.8443	-16.4460***
internet	332.308***	0.9995	3.083	-11.0011***	26.9876	-13.8821***
regulatory	3.498***	0.4473	-4.2428***		-2.2005**	
gdp	134.350***	0.9562	-10.2340***		-18.4963***	

Source: data processed

We follow Bailey et al (2016) and Bailey et al (2019) method to establish the exponent of CSD in a panel with many observations, N cross-sectional units over T time. The exponent method estimates the strength of the factor for a residual or multiple variables. Table 2, column 3, presents results related to exponent CSD, alpha statistics. Except for political stability and regulatory variables, alpha is above 0.5 for all variables, indicating stronger CSD. Furthermore, the results imply that changes or trends in these variables are strongly related across the different countries; the variables tend to move together or are influenced by similar factors. Moreover, alpha is below 0.5 for political stability and regulatory variables, suggesting that they exhibit weaker CSD, indicating that the variables may not be closely related or influenced by the same factors across the different countries in the panel.

4.2. Unit root and cointegration tests

This study utilized the first-generation panel unit root tests, such as Levin-Lin-Chun (LLC), Im-Pesaran-Shin (IPS), and Breitung, to find out whether a panel data series is stationary or contains unit roots. A unit root stipulates that the variable has a time-dependent structure, implying that shocks to the system do not dissipate over time and the series is non-stationary. The LLC test presumes that all units in the panel split a common unit root process, while the IPS test allows for the prospect that each country in the panel may have its unit root process, whereas the Breitung test assumes the existence of a recurrent unit root across the panel (Breitung, 2000; Im et al., 2003; Levin et al., 2002). Table 2 Column 4 presents results related to LLC, all variables significantly reject the proposition at the level that implies covariates are stationary and do not contain a unit root. The result stipulates that if a variable is stationary at the level, it follows a stable, long-term path, and shocks to the system will not cause permanent deviations. Table 2, Columns 5-8 present results related to IPS and Breitung at the level and first difference. Hypothesis is discarded at the level for variables like natural resource, governance, and GDP, indicating that these variables do not exhibit a unit root and their values fluctuate around a stable mean over time. However, we reject the null hypothesis at the first difference for variables such as renewable energy consumption, broad money, and digital technology, indicating that these variables are unsteady at levels. This implies that initial levels of these variables exhibit trends or patterns that cause them to drift over time, while the resulting series becomes stationary when subtracting the previous period's values.

Table 3. Second-generation panel unit root tests

Variables	CIPS		CADF	
	Level	First Difference	Level	First Difference
rec	-2.245	-4.197***	-1.774	-3.125***
broad	-2.162	-4.186***	-1.989	-2.968***
natural	-2.329	-3.952***	-2.281	-3.070***
fts	-2.442	-3.594***	-	-2.514***
mbs	-2.711***	-	-2.995***	-
internet	-2.050	-3.505***	-2.172	-2.579***
regulatory	-	-3.040***	-	-2.601***
gdp	-	-3.335***	-	-2.564***

Noted: ***, **, and * significantly at 0.01, 0.05, and 0.1: Both CIPS and CADF tests have the null hypothesis that panels in the dataset have a unit root.

While unit root testing of the first-generation is useful in detecting unit roots and testing for immobility in panel data, it comes with certain assumptions, notably that cross-sectional units in the panel are distinct from each other. However, in many real-world applications, especially in economics, CSD often exists. This violates the assumptions of first-generation tests, leading to potential biases and inaccurate conclusions. In this study, we employ the second-generation panel unit root tests, such as cross-sectional IPS (CIPS) and augmented Dickey-Fuller (CADF), which are developed to address this issue by accounting for CSD between economies in the panel (Westerlund & Hosseinkouchack, 2016). Table 3 Columns 2 and 3 present results related to CIPS, renewable energy consumption, broad money, natural resources, fixed telephone, and internet usage reject the null hypothesis at first difference, while other variables are at the level. Results indicate that the variables are stationary across the panel, at level and first difference, even when accounting for CSD, which indicates that the series does not have a unit root, and the cross-sectional countries do not exhibit random walks or permanent shocks. Table 3, Columns 4 and 5, presents results related to CADF and account for CSD by including cross-sectional averages of other series. Renewable energy consumption, broad money, natural resources, and the internet reject the null hypothesis at first difference indicate that, the data series do not exhibit a unit root after a period difference and results hold even when the cross-sectional correlation is present implying that the series will revert to a long-term mean and shocks will dissipate over time. This finding provides a sound econometric basis for subsequent long-run and causality analyses.

Westerlund (2007) proposed a panel co-integration test to explore whether a long-run equilibrium association exists between variables in panel data. The four-panel cointegration tests assess whether divergence from this long-run association is corrected over time. All four test statistics reject the proposition that there is no association across variables for all panels and suggest that at least various cross-sectional units exhibit cointegration and, hence, share a long-run equilibrium relationship. Results imply that even though short-term deviations may occur, the presence of a long-run equilibrium verdict that the covariates tend to return to over time. Variables under this study move together in the long run despite short-term fluctuations. Moreover, it suggests that policies or economic variables are linked over time rather than moving independently.

4.3. Endogeneity and the dynamic effect of renewable energy consumption and the error term

This study utilized a dynamic panel data (DPD) model estimated using the two-step generalized method of moments (GMM) estimator suggested by Arellano & Bond (1991) to examine the dynamic relationship. The dynamic specification accounts for a likely endogeneity of the explanatory predictors by including a lagged dependent covariate among the regressors. The inclusion introduces an association between the lagged dependent covariate and the error term, which renders standard fixed-effects estimators biased and inconsistent (Rakshit, 2022). The GMM estimator addresses this concern by employing a suitable lagged estimate of the endogenous variables as instruments. A two-step GMM estimator is preferred for its asymptotic efficiency, as it uses the residuals from the one-step estimation to fabricate an optimal weighting matrix. To correct for potential finite-sample downward bias in the estimated standard errors, we report robust standard errors, adjusted using the (Windmeijer, 2005) correction. Table 4 presents results related to a baseline model; The estimate of the lagged dependent variable, consumption of renewable energy, is significant and statistically positive across all model specifications. The result confirms the presence of strong state dependence in renewable energy usage, indicating that previous consumption levels are a key determinant of current consumption. Furthermore, countries with higher levels of renewable energy consumption in the preceding period are more probably to sustain or increase their consumption in the current period.

Broad money exhibits a significantly negative relationship with fixed telephone subscriptions while showing a notably positive association with mobile phone subscriptions and internet users. This suggests that increasing liquidity in the financial system is more closely aligned with investment in and uptake of modern and flexible digital technologies rather than with legacy infrastructure such as fixed-line telephony. It reflects a shift in digital connectivity patterns, particularly in emerging economies, where mobile and internet access have leapfrogged traditional communication channels. Conversely, natural resource rents reveal a significant benefit on renewable energy consumption, however, individual indicators of internet usage, fixed telephone, and mobile phone subscriptions exhibit a negative association. The divergence implies that while resource-rich countries may invest directly or indirectly in renewable energy, possibly due to resource-financed development or environmental policy shifts, they may simultaneously exhibit weaker investment in or slower diffusion of digital infrastructure, potentially due to rent-seeking behaviour, institutional weaknesses, or an overreliance on extractive sectors.

Moreover, when using a composite measure of digitalization, the effect becomes significantly positive, indicating that while individual digital indicators may show inconsistent signs, a more integrated and holistic measure of digital advancement is positively associated with renewable energy consumption. Coefficients of individual indicators of digitalization, fixed telephone subscriptions, mobile phone subscriptions, and internet usage are significantly negative, implying that digital connectivity facilitates greater access to information, smart energy solutions, and decentralized renewable technologies. The counterintuitive result implies that already highly digitalized countries may not experience diminishing marginal benefits from further digital expansion in terms of renewable energy uptake or being more sensitive to disparities in infrastructure development across countries. The findings suggest that digital infrastructure, when viewed as a system, relax a facilitating character in the expansion of renewable energy, likely through improved energy efficiency. Regulatory quality is found to be significantly positive, which may not reflect structural or implementation gaps in countries with formal regulations but limited enforcement capacity, or it may not indicate that, in some contexts, more stringent regulation correlates with bureaucratic inefficiencies that slow renewable energy adoptions. Alternatively, the positive sign might not capture the transition phase of reform, where regulatory changes disrupt existing systems before yielding long-term benefits. Strong institutions may encourage investment, ensure enforcement of renewable policies, and reduce market uncertainty. The negative coefficient for GDP per capita indicates that higher income levels are related to lower shares of renewable energy in total energy usage, which could reflect continued reliance on fossil fuel-intensive infrastructure in wealthier nations or a slower pace of transition relative to lower-income countries that are leapfrogging to clean energy solutions.

4.4. Robustness and Sensivity check in System GMM

In this sub-section, this research utilizes the system generalized method of moments (GMM) for linear dynamic panel data, following the approach suggested by Roodman (2009) to examine the robustness of the study. The estimator is a proportion of an inclusive historical tendency in econometric applications toward estimators with fewer presumptions, such as distributed fixed country impact, with arguments opposed to cross-section models. However, various predictors may be endogenous, and idiosyncratic errors are assumed to be uncorrelated across individuals and may exhibit country-specific intricacies of heteroskedasticity and serial correlation. The instruments are considered to be internally established on the lags of the instrumented predictors and the estimator employed to solve the problem of dynamic panel bias (Nickell, 1981). We expect renewable energy consumption to change with a setback to alternative factors such as an economy's financial liquidity, natural resources wealth, digital adoption, regulatory quality, and economic performance. The adjustment process to changes in the covariates considered may depend on lagged versions of predictors and the difference between the stable renewable energy consumption level and the preceding period's definite level, arguments for a dynamic framework.

Table 5 presents results related to the dynamic panel data linear GMM estimator. The result of one-period lagged renewable energy is significant and positive, consistent with the main model results. This confirms the presence of dynamic effects and supports the idea that renewable energy consumption evolves gradually over time in response to changes from selected covariates. Broad money is significant and negative, indicating that when controlling for endogeneity more carefully and using internal instruments, higher financial liquidity may reduce renewable energy consumption. This contrasts with the main model finding (positive effect) and may imply that, in certain contexts, liquidity is directed more towards conventional, carbon-intensive sectors than towards renewables, particularly if financial systems lack green incentives. Natural resource rents are significant and negative only when interacting with internet use, as shown in column (3); otherwise, they are not significant with other digital indicators. This finding weakens the previous positive relationship and suggests that resource wealth does not consistently promote renewable energy once deeper endogeneity issues are controlled for. The negative interaction with internet use may indicate that resource-rich economies with widespread internet access still prioritize extractive industries over renewables. Digitalization remains a significant enabler for renewable energy when broken down into specific channels. However, regulatory quality is generally positive and significant, except with fixed telephone subscriptions, where it is not significant. This implies that better governance tends to foster renewable energy growth, but its influence is weaker when considering outdated technologies like fixed-line telephony. GDP per capita remains significantly negative, consistent with the model, corroborating that higher income alone does not guarantee a shift towards renewables and may reflect persistent reliance on mature fossil-fuel energy systems in wealthier countries.

4.5. Alternative measure of Financial Liquidity

To corroborate the robustness of this research findings, broad money complemented with domestic credit to the private sector (% of GDP) provided by banks as an alternative proxy for monetary liquidity. The indicator captures the actual flow of credit available to private firms and households, offering a more targeted perspective on how financial development supports real economic activities, including investment in renewable energy (Vatamanu & Zugravu, 2023). Unlike broad money, which reflects the overall money supply, domestic credit focuses specifically on productive financing. Using this alternative indicator allows us to test the sensitivity of our results and ensures that our conclusions about the contribution of monetary liquidity in renewable energy consumption are not dependent on the choice of a single financial variable. Table 6 presents the robustness results, using credit provided to the private sector as an alternative liquidity measure, corroborating the key patterns observed in the main model while offering sharper insights. The findings suggest that natural resource wealth, strong regulatory quality, and broader digital adoption continue to positively drive renewable energy consumption, reinforcing the critical role of governance and technological integration in supporting the energy transition. Specifically, natural resource wealth provides the financial and physical capacity to invest in renewable infrastructure, while high regulatory quality ensures policy stability, effective implementation, and investor confidence.

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Table 4. Linear DPD estimation results

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.rec	0.948***	0.909***	0.938***	0.922***	0.950***	0.891***	0.935***	0.914***
	(0.000927)	(0.00127)	(0.000785)	(0.00157)	(0.000533)	(0.00133)	(0.00114)	(0.00121)
broad	-0.00904***	0.0133***	0.00748***	0.00947***	-0.00597***	0.00949***	0.00726***	0.00705***
	(0.000410)	(0.000213)	(0.000327)	(0.000270)	(0.000312)	(0.000424)	(0.000275)	(0.000536)
natural	0.0543***	0.135***	0.0838***	0.110***	0.0889***	0.0344***	0.0748***	0.0329***
	(0.000855)	(0.00132)	(0.00118)	(0.00109)	(0.00180)	(0.00374)	(0.00286)	(0.00143)
broad*natural					-0.000896***	0.00326***	0.000221**	0.00247***
					(3.99e-05)	(0.000140)	(9.04e-05)	(5.21e-05)
fts	-0.0131***				-0.0212***			
	(0.000590)				(0.00147)			
mbs		-0.0112***				-0.0151***		
		(0.000184)				(0.000205)		
internet			-0.0121***				-0.0130***	
			(0.000196)				(0.000236)	
digital				0.560***				0.746***
				(0.0101)				(0.0110)
regulatory	0.0371***	0.0258***	0.0176***	0.00702***	0.0359***	0.0382***	0.0189***	0.0100***
	(0.000637)	(0.000638)	(0.000898)	(0.000468)	(0.000609)	(0.000910)	(0.000794)	(0.000570)
gdp12	-0.0921***	-0.106***	-0.0950***	-0.101***	-0.0912***	-0.111***	-0.0959***	-0.103***
	(0.000497)	(0.000614)	(0.000461)	(0.000779)	(0.000797)	(0.000589)	(0.000751)	(0.000879)
Arellano-Bond test for zero autocorrelation in first-differenced errors								
Order 1	-5.4622***	-5.5058***	-5.4634***	-5.4725***	-5.4488***	-5.5636***	-5.4724***	-5.5217***
Order 2	0.0090	-0.0521	-0.0456	-0.0358	-0.0175	0.0239	-0.0421	0.0374
Sargan test of overidentifying restrictions								
Chi2	119.6738	119.8508	122.0011	119.5908	118.9297	1200.4679	117.5239	123.2262
Wald chi2	5.32e+07***	2.46e+08***	3.27e+08***	9.55e+07***	2.58e+07***	2.25e+06***	1.74e+07***	9.39e+07***
Time variable (year)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356	2,356	2,356	2,356	2,356
Number of c_id	124	124	124	124	124	124	124	124

Noted: Standard errors in parentheses; Renewable energy consumption used as instrument for differenced equation, GMM-type; broad and natural used as instruments for level equation.

Table 5. Dynamic panel data linear GMM estimator results

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.rene_cons	0.992***	0.992***	0.993***	0.994***	0.992***	0.991***	0.993***	0.994***
	(0.00107)	(0.000908)	(0.000855)	(0.00186)	(0.00137)	(0.000946)	(0.000919)	(0.00166)
broad	-0.00166***	-0.000744*	-0.00232***	-0.00108***	-0.00104**	-0.000392	-0.00192***	-0.000963**
	(0.000325)	(0.000448)	(0.000585)	(0.000325)	(0.000435)	(0.000560)	(0.000504)	(0.000383)
natural	-0.00126	-0.00149	-0.00335***	-0.00156	0.00261	0.000661	0.000107	-0.000948
	(0.00105)	(0.00124)	(0.00109)	(0.000977)	(0.00229)	(0.00307)	(0.00178)	(0.00299)
broad*natural					-7.84e-05**	-8.34e-05	-9.00e-05**	1.56e-07
					(3.91e-05)	(6.11e-05)	(3.51e-05)	(4.57e-05)
fts	0.00843***				0.00830***			
	(0.00124)				(0.00161)			
mbs		-0.000216				-0.000218		
		(0.000155)				(0.000167)		
internet			0.00576***				0.00555***	
			(0.000521)				(0.000650)	
digital				0.0364*				0.0435***
				(0.0194)				(0.0142)
regulatory	0.00284***	0.00490***	0.00169**	0.00437***	0.00204	0.00515***	0.00152**	0.00381***
	(0.000963)	(0.000571)	(0.000753)	(0.000948)	(0.00124)	(0.000578)	(0.000759)	(0.000922)
gdp	-0.0410***	-0.0391***	-0.0374***	-0.0422***	-0.0405***	-0.0408***	-0.0383***	-0.0411***
	(0.00117)	(0.00178)	(0.00131)	(0.00110)	(0.00168)	(0.00179)	(0.00189)	(0.00128)
Arellano-Bond test for AR in first difference								
Order 1	-5.38***	-5.38***	-5.39***	-5.38***	-5.38***	-5.38***	-5.38***	-5.38***
Order 2	0.14	0.15	0.16	0.14	0.14	0.14	0.16	0.14
Sargan test of overidentifying restrictions								
Chi2	723.34***	722.82***	717.59***	723.10***	723.52***	723.00***	717.76***	723.23***
Hansen Test of overidentifying restrictions								
Chi2	120.66	118.44	121.14	121.34	119.32	121.46	118.77	118.05
Difference-in-Hansen tests of exogeneity of instrument subsets								
Excluding group	120.32	118.44	119.28	121.19	117.36	121.46	119.16	119.68
Number of c_id	124	124	124	124	124	124	124	124

Noted: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 6. Alternative measures of financial liquidity

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.rene_cons	0.934***	0.909***	0.931***	0.920***	0.937***	0.903***	0.931***	0.918***
	(0.000828)	(0.000829)	(0.00114)	(0.000743)	(0.000626)	(0.000777)	(0.00119)	(0.000665)
dcps_banks	-0.0249***	4.24e-05	-0.0168***	-0.00873***	-0.0200***	-0.00316***	-0.0164***	-0.00990***
	(0.000626)	(0.000992)	(0.000433)	(0.000428)	(0.000195)	(0.000932)	(0.000960)	(0.000577)
natural	0.0551***	0.124***	0.0695***	0.100***	0.0804***	0.0869***	0.0788***	0.0807***
	(0.00139)	(0.00258)	(0.000869)	(0.00128)	(0.00127)	(0.00215)	(0.00154)	(0.00242)
dcps_banks*natural					-0.00111***	0.00232***	-0.00048***	0.00118***
					(6.40e-05)	(8.32e-05)	(9.55e-05)	(7.47e-05)
fts	-0.00814***				-0.0144***			
	(0.000816)				(0.000768)			
mbs		-0.00892***				-0.0106***		
		(0.000164)				(9.96e-05)		
internet			-0.00486***				-0.00423***	
			(0.000136)				(0.000171)	
digital				0.387***				0.452***
				(0.00853)				(0.00821)
regulatory	0.0568***	0.0447***	0.0495***	0.0362***	0.0563***	0.0480***	0.0490***	0.0370***
	(0.000900)	(0.00113)	(0.000584)	(0.000664)	(0.000654)	(0.00158)	(0.00114)	(0.00133)
gdp	-0.101***	-0.112***	-0.105***	-0.111***	-0.0997***	-0.119***	-0.104***	-0.111***
	(0.000592)	(0.000638)	(0.000642)	(0.000685)	(0.000562)	(0.000762)	(0.000630)	(0.000626)
Arellano-Bond test for zero autocorrelation in first-differenced errors								
Order 1	-5.4811***	-5.5259***	-5.4948***	-5.5066***	-5.4821***	-5.5679***	-5.4757***	-5.5234***
Order 2	0.0294	-0.0620	-0.0128	-0.0379	0.0171	-0.0629	-0.0108	-0.0347
Sargan test of overidentifying restrictions								
Chi2	116.1745	120.4651	119.4787	117.4004	123.277	118.4998	116.9833	120.2982
Wald chi2	3.27e+07	4.28e+06	1.58e+07	1.28e+07	3.00e+07	3.56e+07	1.54e+07	4.02e+07***
Time variable (year)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356	2,356	2,356	2,356	2,356
Number of c_id	124	124	124	124	124	124	124	124

Noted: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

However, the negative and significant effects of the alternative liquidity measure, the interaction between natural resources and liquidity, individual digital adoption indicators (internet use, mobile phone, and fixed telephone subscriptions), and GDP per capita reveal deeper structural challenges. These results imply that merely expanding financial credit or basic digital access is insufficient; without coordinated policy frameworks and strategic targeting, financial flows and technological expansion may inadvertently reinforce traditional energy structures rather than catalyse the shift toward renewables. Moreover, the findings underline a crucial policy key point: natural wealth, smart regulation, and integrated digital ecosystems are powerful enablers of renewable energy, but the quality and direction of financial progress and digital investments matter far more than their sheer quantity. Rather than expansion alone, strategic alignment is key to accelerating sustainable energy transitions.

4.6. Nonlinear Moment Condition

In this sub-section, two-step GMM estimators for the linear dynamic panel data model, as proposed by Ahn & Schmidt (1995), builds on the Arellano & Bond (1991) framework but refinements in using nonlinear moment conditions under homoscedasticity, strict exogeneity, and no serial correlation in the idiosyncratic error term. Rather than relying solely on linear moment conditions, the proposed estimator utilizes nonlinear (quadratic) moment conditions to exploit homoscedasticity and no serial correlation that involves the form $E(\Delta\epsilon_{it}\epsilon_{it-1}) = 0$ and higher-order nonlinear transformations $E({\epsilon_{it}}^2 - {\epsilon_{it-1}}^2) = 0$. The nonlinear conditions increase the number of valid instruments and can lead to efficient GMM estimators under the stated assumptions. The estimator uses a consistent initial estimator, usually based on initial changed equations and decreased levels as tools, and residuals used from step one to construct unequal variance-robust weighting matrix, then re-estimates the parameters for improved efficiency (Windmeijer, 2005). The forward orthogonal deviations are utilized, whereas the two-step estimator uses an optimal weighting matrix that is estimated based on the one-step residuals.

Table 7 presents results related to the nonlinear moment condition of linear dynamic panel data. The substantial coefficient of one-period lag renewable energy consumption, consistent with the linear model, reinforces the dynamic nature of renewable adoption: past consumption patterns persist, reflecting inertia in infrastructure development, investment flows, and policy implementation. The negative significant relationship between broad money and fixed telephone subscriptions, positive with mobile phone subscriptions, and insignificance with internet and digital index reveals a heterogeneous financial effect across technological channels. It implies that financial liquidity may support renewables only where modern, mobile-based digital infrastructure exists, while being ineffective, or even detrimental, when tied to outdated systems. Natural resource rents and the interaction term are insignificant, weakening the resource-led hypothesis for renewables in this specification. Suggests that without targeted policy frameworks or investment channels, natural wealth alone does not drive clean energy adoption, particularly in nonlinear dynamics.

The individual digital indicators being negative and significant, while the composite digital index is positive and significant, suggests a nonlinear, threshold-like effect: piecemeal digital adoption may not drive renewables on its own and, in some cases, may reflect lagging infrastructure or usage patterns. However, when digital tools are developed in an integrated, synergistic manner, their collective impact becomes transformative for renewable energy systems. Regulatory quality is negative and insignificant with fixed telephone subscriptions, suggesting that governance quality has limited influence when outdated infrastructure is the dominant form of connectivity. However, notable positive effects with mobile phone subscriptions, internet use, and the composite digital index imply that good regulatory environments enhance the influence of modern digital infrastructure on the consumption of renewable energy. This underscores the role of governance in enabling smart, flexible energy systems reliant on contemporary technologies. The consistent negative and significant coefficient of economic performance reaffirms a key trend across models: higher income levels do not automatically lead to more renewable energy consumption. This may indicate that wealthier countries, especially resource-rich ones, often remain locked into legacy fossil fuel systems without strong policy redirection.

4.7. Policy Implication

This research presents to the growing body of knowledge that highlights the complex nature of the energy transition, extending beyond traditional economic and environmental factors. By examining financial liquidity, digital advancement, institutional quality, and reliance on natural resources within a dynamic panel context, it provides a more comprehensive view of the systemic elements that either foster or limit the adoption of renewable energy. These findings are especially pertinent for policymakers in developing and resource-abundant nations where institutional and financial frameworks are rapidly evolving.

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Table 7. Nonlinear moment condition result

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.rene_cons	0.904***	0.947***	0.910***	0.911***	0.904***	0.939***	0.894***	0.902***
	(0.0232)	(0.0146)	(0.0186)	(0.0225)	(0.0221)	(0.0127)	(0.0195)	(0.0203)
broad	-0.0246***	0.0214***	-0.00832	-0.00847	-0.0246**	0.0210***	-0.00605	-0.00838
	(0.00934)	(0.00708)	(0.00666)	(0.00902)	(0.00985)	(0.00759)	(0.00631)	(0.00703)
natural	-0.0216	0.0155	-0.0141	-0.00984	-0.0119	0.0275	0.000458	0.00115
	(0.0146)	(0.0158)	(0.0136)	(0.0129)	(0.0202)	(0.0172)	(0.0156)	(0.0165)
broad_natural					-0.000317	-0.000425	-0.000469	-0.000487
					(0.000458)	(0.000339)	(0.000370)	(0.000414)
fts	-0.0362***				-0.0309***			
	(0.0136)				(0.0120)			
mbs		-0.00372*				-0.00341		
		(0.00206)				(0.00216)		
internet			-0.00898**				-0.0103***	
			(0.00368)				(0.00390)	
pc2				0.255**				0.280**
				(0.125)				(0.135)
regulatory	-0.0122	0.0228***	-0.0219*	-0.0235*	-0.0103	0.0266***	-0.0186*	-0.0228*
	(0.0129)	(0.00685)	(0.0125)	(0.0125)	(0.0112)	(0.00837)	(0.0112)	(0.0117)
gdp12	-0.0539***	-0.0278**	-0.0500***	-0.0486***	-0.0553***	-0.0252**	-0.0502***	-0.0509***
	(0.0159)	(0.0127)	(0.0150)	(0.0143)	(0.0163)	(0.0116)	(0.0148)	(0.0146)
Arellano-Bond test for autocorrelation of the first-differenced residual								
Order 1	-5.5130***	-5.5201***	-5.6440***	-5.7105***	-5.6429***	-5.5174***	-5.6662***	-5.6463***
Order 2	0.1861	0.1163	0.1529	0.1803	0.1722	0.1120	0.1316	0.1619
Sargan-Hansen test for the overidentifying restrictions								
Chi2	118.1556	122.2283	119.0678	115.1343	118.9465	119.2354	120.1769	119.3860
Convergence	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356	2,356	2,356	2,356	2,356
Number of c_id	124	124	124	124	124	124	124	124

Noted: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

The results indicate that monetary liquidity, in line with Jie et al (2024), may produce ambiguous or even adverse impacts on renewable energy consumption if not appropriately aligned with green investment goals. The role of monetary liquidity in supporting digital infrastructure, especially mobile and internet-based technologies, points to the need for financial policies that enable access to capital for digital innovation and clean energy technologies. Policymakers should consider facilitating credit access and financial instruments tailored to the digital and renewable energy sectors. Moreover, policy must direct monetary expansion and credit growth towards sustainable sectors using targeted tools such as concessional loans and credit guarantees for renewable energy projects. In the absence of clear policy guidance, financial resources could continue to favour fossil fuel-dependent sectors, undermining the potential of monetary policy in achieving climate objectives.

Contrary to the conventional resource curse hypothesis, the findings suggest that natural resource rents do not inherently hinder renewable energy consumption, especially under strong regulatory frameworks and digital integration. Underscores the importance of institutional mechanisms that redirect resource revenues towards long-term sustainability, such as green infrastructure financing or decarbonization subsidies. Resource-rich economies must adopt forward-looking policies that leverage natural wealth for structural transformation rather than reinforcing energy dependence. Policymakers should prioritise comprehensive digital strategies that integrate telecommunications, internet accessibility, and digital literacy as enablers of renewable energy adoption. Fragmented or uncoordinated digital growth may fail to deliver the transformational benefits required for sustainable energy systems. In line with (Vatamanu & Zugravu, 2023), regulatory quality consistently emerges as a substantial driver of consumption of renewable energy, suggesting the need for explicit, predictable, and innovation-friendly policy environments that reduce uncertainty for investors and accelerate the deployment of renewables. Governments must strengthen governance frameworks, improve the rule of law, reduce bureaucratic hurdles, and ensure accountability in energy policy implementation to create the enabling conditions for clean energy growth. Higher-income countries must actively decouple growth from fossil fuel dependence by setting ambitious renewable targets and promoting clean energy investments.

5. Conclusion

This study challenges the conventional view that natural resource wealth and financial constraints inherently hinder renewable energy adoption, revealing instead that, with the right financial systems, digital infrastructure, and institutional frameworks, these factors can be powerful enablers of sustainable energy transitions. By integrating insights from Energy Transition Theory (ETT) and Ecological Modernisation Theory (EMT), the research demonstrates that financial liquidity and natural resource wealth, when strategically mobilised, can foster renewable energy consumption, especially in resource-dependent and financially constrained developing economies. Furthermore, the study underscores that digitalisation and good governance are critical to translating financial flows into effective renewable energy investments. Bridging gaps left by prior literature, this research offers a multidimensional framework for understanding how economic, technological, and corporate levers interact in shaping the universal shift toward cleaner energy systems. This dynamic panel data model was employed to capture the evolving relationships among the set of selected drivers over time. The findings challenge the traditional resource curse hypothesis, suggesting that under the right governance and policy frameworks, natural resource wealth can be effectively leveraged to promote, rather than inhibit, renewable energy adoption.

Findings indicate that broad money, as a proxy for financial liquidity, can significantly influence renewable energy consumption, while its impact depends on how financial flows are governed and allocated. Moreover, increased liquidity has the potential to stimulate green investments; without targeted financial mechanisms and regulatory support, it may reinforce existing fossil fuel structures. Similarly, the disaggregated analysis of digitalisation shows that specific digital technologies, such as mobile and internet usage, yield more actionable insights than aggregated digital indices, emphasising the importance of targeted technological deployment. Regulatory effectiveness emerges as a consistent enabler of clean energy transition, signifying the need for robust governance to align financial and technological capacity with sustainability objectives. Theoretically, this study contributes to the literature by integrating perspectives from ETT and EMT to build a comprehensive framework that explains how financial systems and natural resources can be directed toward renewable energy development. Empirically, it addresses key gaps by examining both direct and interaction effects of monetary liquidity and natural resource rents, alongside digitalisation and institutional quality. The inclusion of robustness checks using alternative measures of financial flow further strengthens the credibility of the findings. Furthermore, results from the nonlinear moment of two-step GMM stress that digitalisation and financial development must be strategic and synergistic to support renewable energy. Fragmented or outdated infrastructure, untargeted credit expansion, and resource wealth without governance alignment are unlikely to yield sustainable energy transitions. The study highlights that policy coherence, linking regulation, digital infrastructure, and finance, is critical for converting economic and technological capacity into renewable energy outcomes. The research outcomes propose the policy recommendations to promote more effective and inclusive transition to renewable energy, particularly in developing and resource-rich economies: Financial regulators should design monetary policies that explicitly support green investment, ensuring that increased monetary liquidity is channelled into clean energy sectors rather than fossil fuel-intensive industries.

Governments in resource-rich economies should adopt fiscal rules or sovereign wealth fund frameworks that allocate resource revenues toward sustainable development goals, particularly renewable energy infrastructure. Moreover, digital literacy initiatives should be expanded to ensure affordable access to digital tools, especially in rural and underdeveloped regions, to facilitate decentralised energy solutions and user-driven energy management. Strengthen institutional capacity through anti-corruption measures, streamlined bureaucracy, and enforcement of the rule of law to build investor confidence and accelerate clean energy deployment. Nonetheless, the study is not without limitations. The reliance on internal instruments in the GMM framework may weaken under small samples or instrument proliferation, and the macro-level nature of the data restricts insights into micro-level dynamics such as firm or household behaviour. The use of aggregated indicators may also mask important heterogeneities across regions or sectors. These limitations suggest that future research should consider mixed-method or multi-level approaches to capture finer contextual nuances and further validate the pathways uncovered in this study.

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Declarations

Author contribution	:	HSL: Writing – original draft, Writing – review & editing, Conceptualization, Software, Validation, Methodology, Formal Analysis, Data curation, Investigation FET: Writing – review & editing, Validation, Supervision, Investigation CFM: Writing – review & editing, Conceptualisation, Data curation, Project administration.
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