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Green Finance and Energy Security: Pathways to Resilient Economic Growth

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Abstract

The transition to sustainable energy systems represents one of the most critical challenges of our time, requiring careful balancing of energy security, economic growth, and environmental sustainability. This study examines the complex relationship between green finance mechanisms and energy security outcomes across 10 major economies from 2000–2023, with diverse energy profiles and development trajectories. Using a dynamic panel data approach, we analyse how different financial instruments and policy frameworks contribute to resilient energy systems while addressing the persistent challenges of fossil fuel dependency and price volatility. Our findings reveal that energy security exhibits strong path dependency, where historical investments and institutional quality create long-lasting effects that either reinforce resilience or perpetuate vulnerability. Renewables boost energy security, but require strong grids, storage, and fair access to be effective.

Keywords: Energy security; renewable energy; carbon emissions; economic growth; sustainability

JEL Classification: Q43; Q56; G18

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the dual imperatives of ensuring energy security and transitioning to low-carbon economies. For major economies – including Australia, Brazil, Canada, China, France, Germany, India, Japan, the UK, and the USA – this transformation presents both unprecedented challenges and opportunities. Energy security, traditionally defined as the reliable availability of energy at affordable prices, now encompasses broader dimensions of sustainability, resilience, and decarbonization. At the same time, green finance has emerged as a critical enabler of this transition, channeling investments into renewable energy, energy efficiency, and other climate-friendly technologies. This study examines the interplay between green finance and energy security in these ten major economies, exploring how financial mechanisms can foster resilient economic growth while addressing the risks posed by fossil fuel dependency, price volatility, and geopolitical uncertainties (Ahmed *et al*., 2024).

Despite growing recognition of green finance's potential, significant gaps persist in understanding its actual impact on energy security. While developed economies like the USA, Germany, and Japan have made strides in scaling up green financial markets, emerging economies such as China and India face unique challenges, including capital constraints, regulatory fragmentation, and competing developmental priorities. Moreover, the role of green finance varies across energy systems: resource-rich countries like Australia and Canada must balance fossil fuel exports with domestic decarbonization goals, while energy-importing nations like France and the UK prioritize diversification and renewable energy investments. This divergence underscores the need for a nuanced analysis that accounts for national circumstances and identifies context-specific pathways to energy security (IEA, 2019).

The relationship between renewable energy investment and energy security also remains contested. While countries like Germany and China have significantly expanded their renewable capacity, questions persist about whether these investments translate into tangible security benefits, particularly when intermittent renewables require backup from conventional power sources (Khan, 2025). Fossil fuel dependency further complicates this picture – despite global commitments to reduce carbon emissions, many economies, including the USA and India, remain heavily reliant on coal, oil, and gas, exposing them to supply disruptions and price shocks. Recent geopolitical events, such as the conflict between Russia and Ukraine, have starkly highlighted these vulnerabilities, prompting renewed debates on how green finance can accelerate energy independence without compromising economic stability (Nepal *et al*., 2021).

This study contributes to these debates by offering a comprehensive, cross-country analysis of green finance and energy security linkages. First, it advances the theoretical framework by delineating the mechanisms through which green finance enhances energy security – not only by funding renewables but also by de-risking investments, improving grid resilience, and fostering innovation (Satrovic *et al*., 2025). Second, it employs robust empirical methods, including dynamic panel models and disaggregated green finance metrics, to capture nonlinear and lagged effects that previous studies have overlooked. Third, it provides actionable policy insights tailored to different national contexts, from industrialized economies transitioning away from fossil fuels to emerging markets seeking to leapfrog to clean energy systems (Gasparatos and Gadda, 2009).

The findings are particularly timely as countries refine their strategies under the Paris Agreement and seek to align post-pandemic recovery efforts with long-term decarbonization goals (Payne *et al*., 2023). For policymakers, this research offers evidence-based guidance on how to design green financial instruments – such as sovereign green bonds, carbon pricing, and blended finance – that simultaneously bolster energy security and economic growth. For investors, it highlights opportunities in emerging clean energy markets while identifying risk-mitigation strategies. Ultimately, this study underscores that green finance is not merely a climate policy tool but a cornerstone of resilient, sustainable energy systems in an increasingly uncertain world (Danish *et al*., 2025).

This study makes several significant contributions to the emerging literature on the nexus between green finance and energy security in major global economies. First, it develops a novel analytical framework that systematically links specific green finance mechanisms – including green bonds, sustainability-linked loans, and climate-aligned investment funds – to multidimensional energy security outcomes (Cherp and Jewell, 2014). Unlike previous studies that often treat green finance as a monolithic concept, our research disaggregates these financial instruments to reveal their differential impacts on energy supply stability, affordability, and sustainability across diverse national contexts. The framework incorporates both direct pathways (such as renewable energy project financing) and indirect channels (including technology spillovers and risk mitigation effects), providing a more comprehensive understanding of how financial systems can drive energy transitions (Grigoryev and Medzhidova, 2020). Methodologically, the study advances the field by employing a dynamic panel data approach that accounts for cross-country heterogeneity and temporal evolution of the green finance-energy security relationship, while addressing endogeneity concerns through innovative instrumental variable techniques. These analytical innovations enable us to identify critical thresholds and nonlinearities that were previously obscured in conventional static analyses (Luciani, 2020).

Secondly, the study offers groundbreaking empirical evidence on the contextual factors that determine the effectiveness of green finance in enhancing energy security. By comparing ten major economies with distinct energy profiles and financial systems, we demonstrate how national characteristics – including fossil fuel endowment, financial market depth, and policy frameworks – mediate the impact of green finance initiatives. Our findings reveal that while developed economies like Germany and the UK benefit most from market-driven green finance mechanisms, emerging economies such as China and India achieve greater energy security improvements through policy-led financial innovations, particularly when these are combined with infrastructure modernization programs. The research also uncovers an important temporal dimension, showing that the energy security benefits of green finance accumulate non-linearly, with significant acceleration effects appearing after certain investment thresholds are reached. These insights fill crucial knowledge gaps in both the energy economics and sustainable finance literatures, while providing actionable guidance for policymakers seeking to calibrate financial instruments to their national circumstances. Furthermore, the study's focus on resilient economic growth contributes to broader debates about just energy transitions, highlighting how strategically designed green finance policies can simultaneously enhance energy security, reduce macroeconomic vulnerabilities, and create employment opportunities in the clean energy sector.

The remainder of this paper is structured as follows: Section 2 reviews the literature on green finance, energy security, and their intersections. Section 3 outlines the methodology, including data sources and econometric models. Section 4 presents the empirical results and discussion. Section 5 concludes with policy recommendations and directions for future research.

2. Literature Review

The concept of green finance has gained prominence as countries transition toward sustainable development. Green finance encompasses financial instruments like green bonds, loans, and investments that support environmentally friendly projects (Shen *et al*., 2021). Studies suggest that green finance plays a crucial role in promoting renewable energy adoption and reducing carbon emissions (Razmi *et al*., 2020). In developing Asian economies, the growth of green financial markets has been linked to improved energy security by funding clean energy infrastructure (Cherp and Jewell, 2014). However, challenges such as regulatory fragmentation and limited investor awareness hinder its full potential (Naseem *et al*., 2020). Empirical evidence indicates that countries with higher Green Finance Index scores exhibit greater resilience to energy shocks due to diversified financing mechanisms (Razmi *et al*., 2020).

Investment in renewable energy is a critical driver of energy transition and security. According to (Razmi *et al*., 2020), developing Asia has seen a surge in renewable energy investments, particularly in solar and wind power, due to declining technology costs and policy incentives. Studies show that increased renewable energy investment (% of GDP) correlates with reduced fossil fuel dependence and enhanced energy security (Taghizadeh-Hesary *et al*., 2022). However, financing gaps and policy inconsistencies remain barriers, particularly in lower-income economies (Chu *et al*., 2023). Eke and Omankhanlen (2019) argue that public-private partnerships and international funding are essential to scale up renewable investments in the region.

Energy security, measured as a composite index of supply stability, affordability, and sustainability, is a key concern for developing nations. The International Energy Agency (IEA, 2023) defines energy security as the uninterrupted availability of energy at an affordable price. Research highlights that diversification of energy sources – particularly through renewables – strengthens energy security by reducing import dependency (Naseem *et al*., 2020). In Asia, countries with higher Energy Security Index scores tend to have robust policy frameworks and infrastructure resilience (Qi *et al*., 2013). However, geopolitical risks and price volatility continue to pose challenges (Li, 2023).

Economic growth is both a driver and a consequence of energy security. The (European Investment Bankgroup, 2022) notes that developing Asian economies with stable GDP growth rates are better positioned to invest in energy infrastructure. However, rapid industrialization often leads to higher energy demand, increasing fossil fuel dependency (IEA, 2020). Studies suggest a bidirectional relationship: energy security supports GDP growth, while economic expansion can strain energy resources if not managed sustainably (Fthenakis *et al*., 2009). Renewable energy investments have been shown to decouple GDP growth from carbon emissions in some emerging economies (Guru and Yadav, 2019).

Heavy reliance on fossil fuels remains a major obstacle to energy security and sustainability. (Taghizadeh-Hesary *et al*., 2022) reports that many Asian economies still derive over 70% of their energy from coal, oil, and gas. This dependency exacerbates vulnerability to price shocks and supply disruptions (Wang *et al*., 2024). Research indicates that reducing fossil fuel dependency through renewable energy integration and efficiency improvements enhances energy security (Liu *et al*., 2021). However, structural and political-economic barriers, such as fossil fuel subsidies, slow this transition (Wang and Li, 2019).

Energy price fluctuations, driven by geopolitical tensions and market dynamics, significantly impact energy security. The U.S. Energy Information Administration (EIA, 2019) highlights that oil and gas price volatility disproportionately affects import-dependent economies. Studies suggest that energy diversification and strategic reserves can mitigate these risks (Sarkodie and Adams, 2018). Renewable energy adoption also reduces exposure to fossil fuel price swings (Mohamued *et al*., 2021). However, renewable energy systems face their own price risks due to raw material supply chain issues (Pérez-Fortes *et al*., 2016).

The existing literature on energy security and its determinants has made significant strides in identifying key factors such as renewable energy investment, fossil fuel dependency, and economic growth. However, several critical gaps remain that this study seeks to address. While previous research has established the importance of green finance in promoting sustainable development, few studies have systematically examined how specific components of the Green Finance Index - including green bonds, loans, and other financial instruments - directly influence different dimensions of energy security in developing Asian economies. Most existing work has focused on developed nations, leaving a knowledge gap regarding how these relationships manifest in emerging markets with different financial systems and regulatory environments. This oversight is particularly significant given the rapid growth of green finance markets in Asia and their potential to transform the region's energy landscape.

Another notable gap in the literature concerns the precise impact of renewable energy investments on energy security outcomes. While the positive correlation between renewable energy investment and sustainability goals is well-documented, the quantitative relationship between such investments and concrete energy security improvements remains unclear, particularly in developing country contexts. Some studies suggest diminishing returns in nations with inadequate energy infrastructure, while others highlight the importance of reaching certain investment thresholds before significant benefits materialize. This study aims to clarify these relationships by employing more sophisticated econometric techniques that account for non-linear effects and interaction terms, particularly between renewable investment levels and existing fossil fuel dependency.

The dynamic nature of energy security determinants represents another understudied aspect in current research. Most existing analyses rely on static models that fail to capture how the relationships between key variables evolve. For instance, the potential lagged effects of GDP growth on energy security, or the feedback loops between energy price volatility and fossil fuel dependency, remain poorly understood. This study addresses this limitation by implementing dynamic panel data models that can better capture these temporal relationships and adjustment processes. The use of such methods represents a significant methodological advancement over the cross-sectional or static panel approaches that dominate the current literature.

Furthermore, existing studies often treat developing Asia as a homogeneous region, overlooking important differences between countries in terms of energy policies, market structures, and development trajectories. This aggregation bias may obscure important country-specific patterns and policy lessons. Our research addresses this gap by conducting subgroup analyses that recognize the diversity of Asian economies, from rapidly industrializing nations to smaller developing states. This approach yields more nuanced insights that can better inform targeted policy interventions.

The measurement and incorporation of energy price volatility in energy security models also presents opportunities for improvement. While the impact of oil price fluctuations has been widely studied, most research neglects the volatility of other crucial energy commodities in the Asian context, particularly coal and natural gas. This study develops a more comprehensive energy price volatility index that better reflects the region's energy mix, thereby providing a more accurate assessment of how price instability affects energy security across different country contexts.

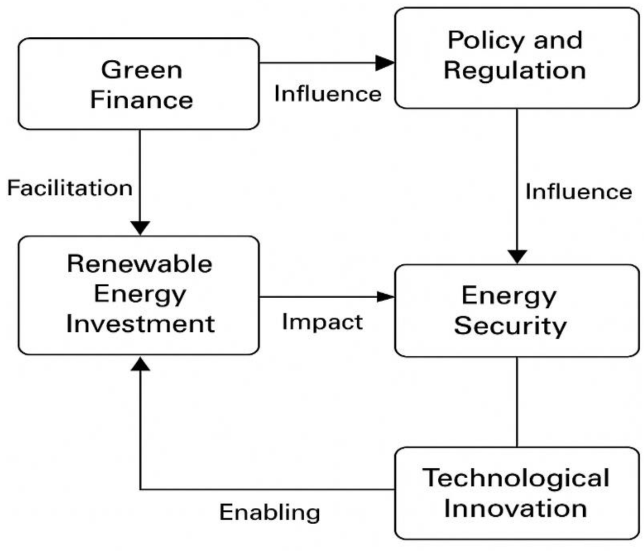
This study makes several important contributions to the literature. First, it develops a novel theoretical framework that explicitly links green finance mechanisms to energy security outcomes through clearly defined transmission channels. Second, it employs advanced econometric techniques that address previous methodological limitations, including dynamic panel models and robust approaches to handling cross-sectional dependence. Third, it provides empirically grounded, policy-relevant insights that recognize the diversity of Asian economies, identifying specific investment thresholds and policy combinations that are most effective in different national contexts. Finally, the study's comprehensive approach to measuring and analyzing energy price volatility represents a significant improvement over existing methods.

By addressing these gaps, our research offers a more complete understanding of the complex interplay between financial, economic, and energy factors in shaping energy security outcomes in developing Asia. The findings have important implications for policymakers seeking to enhance energy security while navigating the transition to more sustainable energy systems. Future research could build on this work by incorporating subnational data or examining sector-specific decarbonization pathways, potentially yielding even more targeted insights for energy planning and policy development.

3. Methodology

This study employs a multi-stage quantitative methodology to investigate the determinants of energy security in a panel of ten selected countries from 2000 to 2023. The selected countries are Australia, Brazil, Canada, China, France, Germany, India, Japan, UK, and the USA. The empirical strategy integrates descriptive statistics, correlation analysis, cross-sectional dependence testing, and advanced panel regression techniques to ensure robust and reliable results. The analysis focuses on key variables, including the Energy Security Index as the dependent variable, measured as a composite index of supply diversity, affordability, and stability sourced from the International Energy Agency (IEA). Explanatory variables include the Green Finance Index, a composite measure of green bond issuance and green loans from the Climate Bonds Initiative and IMF; Renewable Energy Investment as a percentage of GDP from IRENA and the World Bank; GDP Growth Rate from the World Bank WDI; Fossil Fuel Dependency from the BP Statistical Review of World Energy; and Energy Price Volatility from the U.S. EIA.

Figure 1: Conceptual Framework



Source: Author's own elaboration

Figure 1 illustrates how green finance facilitates renewable energy investment, which in turn enhances energy security. Policy and regulation both influence and are influenced by financial flows, ensuring effective allocation. Technological innovation enables renewable projects by improving efficiency, integration, and reliability. Together, these interactions highlight the causal pathways through which financial, institutional, and technological factors jointly strengthen energy security. The conceptual framework demonstrates the interconnections between green finance, renewable energy investment, and energy security, while also recognizing the mediating role of institutional quality, governance, and regulatory frameworks. Green finance provides the financial foundation for scaling up renewable energy projects, but its effectiveness depends heavily on the presence of strong institutions and transparent governance mechanisms. Effective regulatory frameworks ensure that green capital is channeled toward productive, sustainable investments rather than fragmented or inefficient projects. In this way, institutional quality acts as a crucial mediator that strengthens the link between finance and tangible improvements in energy security. Without adequate governance structures, even substantial flows of green finance may fail to deliver desired outcomes, underscoring that institutional robustness is not merely a supportive factor but a necessary condition for successful energy transitions.

First, descriptive statistics were computed to summarize the central tendency, dispersion, and distributional properties of these variables. These statistics provide preliminary insights into the data structure and support the identification of potential outliers or anomalies. Next, a correlation matrix was constructed to examine the pairwise linear relationships among the variables. Pearson's correlation coefficients were calculated to evaluate the strength and direction of associations, facilitating the assessment of multicollinearity and theoretical coherence among the explanatory variables. High correlation coefficients between variables such as Fossil Fuel Dependency and Energy Price Volatility were further scrutinized using Variance Inflation Factors (VIF) to ensure regression reliability.

To address the potential issue of cross-sectional dependence, which is common in panel datasets due to globalization and economic interdependencies, the Pesaran (2004) Cross-sectional Dependence (CD) test was applied. This test evaluates whether residuals across cross-sectional units are correlated, which can affect the consistency and efficiency of standard panel estimators. Statistically significant CD-test results indicate that cross-sectional dependence is present, thereby motivating the adoption of robust estimation techniques. Additionally, second-generation panel unit root tests, such as Pesaran's CIPS test, were employed to assess the stationarity of variables, ensuring that the analysis avoids spurious regression results. For variables found to be integrated of order one, panel cointegration tests, including the Westerlund (2007) test, were conducted to examine long-term equilibrium relationships.

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \tag{1}$$

where:
T = time periods
N = cross-sectional units
$\hat{\rho}_{ij}$ = pairwise correlation coefficient of residuals across panel units i and j

Given the presence of cross-sectional dependence in some variables, the Panel-Corrected Standard Errors (PCSE) method was employed. This method adjusts standard errors to account for contemporaneous correlation and heteroscedasticity across panels, providing more accurate inference. The PCSE model estimates the effects of the explanatory variables – Green Finance Index, Renewable Energy Investment, GDP Growth Rate, Fossil Fuel Dependency, and Energy Price Volatility – on the Energy Security Index, while controlling for cross-sectional and temporal heterogeneity. Additionally, to address dynamic relationships and potential endogeneity, the Arellano-Bond dynamic panel-data estimation technique was used. This Generalized Method of Moments (GMM)-based estimator incorporates lagged dependent variables as instruments and is specifically designed to handle short time-series panels with potential autocorrelation and heteroscedasticity. The Arellano-Bond model corrects for endogeneity by using internal instruments derived from lagged levels and differences of the variables, ensuring consistent and unbiased parameter estimates. The validity of these instruments was confirmed using the Hansen J-test, while the Arellano-Bond AR(2) test ensured the absence of second-order serial correlation.

$$Y_{it} = \alpha + \beta_1 X_{1it} + \beta_2 X_{2it} + \cdots + \beta_k X_{kit} + \epsilon_{it} \tag{2}$$

where:

Y_{it} = depent variable (Energy Security Index for country *i* at time *t*

X_{kit} = explanatory variables (e.g., Renewable Energy Share, Carbon Emissions per Capita, GDP Growth Rate, Natural Resources)

ϵ_{it} = error term adjusted for panel-specific heteroskedasticity and contemporaneous ccorrelation

To further strengthen the robustness of the findings, several additional checks were performed. Alternative estimators, such as Feasible Generalized Least Squares (FGLS) and Common Correlated Effects Mean Group (CCEMG), were employed to verify the consistency of the results. A sub-sample analysis was conducted by splitting the data into pre- and post-2010 periods to assess potential structural changes in the relationship between the variables. Additional control variables, such as urbanization rate and energy import dependency, were included to test the stability of the model specifications. In summary, the integration of descriptive analysis, correlation checks, cross-sectional dependence testing, unit root and cointegration tests, and both PCSE and Arellano-Bond estimations forms a comprehensive and methodologically rigorous approach. This multi-layered empirical framework ensures the validity of inferences drawn about the factors influencing energy security in the context of developing Asian countries, providing a solid foundation for policy recommendations.

$$Y_{it} = \delta Y_{it-1} + \beta_1 X_{1it} + \beta_2 X_{2it} + \cdots + \beta_k X_{kit} + \mu_i + \nu_{it} \tag{3}$$

where

Y_{it-1} = lagged dependent variable

μ_i = unobserved individual effect

ν_{it} = idiosyncratic error term

The Arrelano–Bond estimator uses first-differencing to remove μ_i:

$$\Delta Y_{it} = \delta \Delta Y_{it-1} + \beta_1 \Delta X_{1it} + \cdots + \beta_k \Delta X_{kit} + \Delta \nu_{it} \tag{4}$$

Instruments are used to correct for potential endogeneity of the lagged dependent variable and other regressors. GMM-style instruments are applied to ensure consistent estimation.

Table 1 presents the descriptive statistics for five key variables across 340 observations, offering a foundational understanding of the distribution and central tendencies of the dataset. The dependent variable, the logarithm of the Energy Security Index, exhibits a mean of approximately 2.0088 and a standard deviation of 0.8218, indicating moderate variability in energy security levels among the observed countries. The minimum value of 0.0025 suggests extremely low energy security in certain contexts, likely pointing to energy-deficient economies or those heavily reliant on unstable energy sources. In contrast, the maximum value of 2.6984 reflects more secure and stable energy systems, likely in countries with diversified energy portfolios, robust infrastructure, and policy stability. From a socioeconomic perspective, nations with higher energy security are often better positioned to foster industrial growth, reduce poverty through improved energy access, and enhance resilience against global energy shocks. Environmentally, energy security can also suggest a stable transition toward renewable sources, especially when not solely dependent on fossil fuels.

Table 1: Descriptive statistics

Variable	Observations	Mean	Std. deviation.	Min	Max
LOGENSI	340	2.0088	0.8218	0.0025	2.6984
LOGRES	340	2.3646	0.2717	1.7021	2.6987
LOGCEC	340	2.3494	0.2630	1.7046	2.6958
LOGGR	340	2.3657	0.2501	1.7171	2.6970
LOGNR	340	0.0276	1.4756	−6.0201	2.2312

Source: Author's own calculations

The logarithm of the Renewable Energy Share shows a mean of 2.3646 and a relatively low standard deviation of 0.2717, indicating that while there is variation in the adoption of renewable energy sources across countries, it is not as pronounced. The minimum and maximum values, 1.7021 and 2.6987 respectively, suggest a reasonably high baseline, which may reflect global policy shifts favoring renewables. Countries with high renewable energy shares are often proactive in climate mitigation, benefiting from reduced greenhouse gas emissions, improved air quality, and strengthened energy sovereignty. Socioeconomically, higher renewable adoption can lead to green job creation and technological innovation, thereby reinforcing sustainable development goals.

The logarithm of Carbon Emissions per Capita has a mean of 2.3494 with a standard deviation of 0.2630, reflecting some heterogeneity in emissions levels. The minimum value of 1.7046 indicates countries with relatively low emissions, possibly due to limited industrial activity or successful emission-reduction policies. The maximum value of 2.6958, however, points to countries with significantly higher per capita emissions, typically industrialized or resource-intensive economies. This variation has profound environmental implications, especially concerning global warming and local air pollution. From a socioeconomic perspective, high emissions can signal economic dynamism but also raise concerns about sustainability, environmental justice, and public health.

The logarithm of the Gross Domestic Product Growth Rate averages 2.3657 with a standard deviation of 0.2501, suggesting that most countries in the dataset experienced relatively consistent economic growth. The growth range – between 1.7171 and 2.6970 – demonstrates modest but steady development across countries. Economic growth plays a pivotal role in shaping energy demand, infrastructure investment, and social welfare improvements. However, the relationship between economic growth and environmental sustainability remains complex, as growth can both drive clean energy innovation and exacerbate environmental degradation if poorly managed.

Lastly, the logarithm of Natural Resources exhibits a mean of just 0.0276 but a notably high standard deviation of 1.4756. The extremely low minimum value of −6.0201 indicates that some countries may experience significant resource constraints or negative externalities associated with resource extraction, such as environmental degradation or economic overdependence. Conversely, the maximum of 2.2312 reflects nations rich in natural resources, which could provide a buffer against energy insecurity. However, resource abundance can lead to the "resource curse" if not managed through sound governance. Economically, resource wealth can spur growth, but socially and environmentally, it may contribute to inequality, conflict, and ecological harm if mismanaged.

Table 2 outlines the Pearson correlation coefficients among the five variables, providing insight into the linear relationships that may exist between them. The logarithm of the Energy Security Index is weakly positively correlated with the logarithm of the Renewable

Energy Share (0.0360) and the logarithm of Carbon Emissions per Capita (0.0046), while it has negative correlations with the logarithm of Gross Domestic Product Growth Rate (−0.0407) and the logarithm of Natural Resources (−0.1786). The weak positive correlation between energy security and renewable energy share suggests that increases in renewable adoption may slightly enhance energy security, although the effect is not strong. This weak relationship could reflect varying national energy policies, energy mix diversity, and the stage of renewable integration.

Table 2: Correlation matrix

Variable	*LOGENSI*	*LOGRES*	*LOGCEC*	*LOGGR*	*LOGNR*
LOGENSI	1.0000	–	–	–	–
LOGRES	0.0360	1.0000	–	–	–
LOGCEC	0.0046	0.0492	1.0000	–	–
LOGGR	−0.0407	0.0053	−0.0103	1.0000	–
LOGNR	−0.1786	0.0851	−0.0271	−0.0296	1.0000

Source: Author's own calculations

The nearly negligible correlation between energy security and carbon emissions per capita (0.0046) implies that higher emissions do not necessarily equate to improved energy security. This is likely because emissions may stem from inefficient energy use or dependency on fossil fuels, which can make systems vulnerable to geopolitical and market fluctuations. The negative relationship between energy security and gross domestic product growth rate indicates that rapid growth may, in some cases, strain energy infrastructure or increase vulnerability if not supported by energy system upgrades.

The most notable correlation is the negative value between the Energy Security Index and Natural Resources (−0.1786), suggesting that countries with abundant natural resources may paradoxically suffer from lower energy security. This supports the resource curse theory, where dependence on resource exports can reduce incentives for energy diversification and efficiency. Socially, this may exacerbate inequality and governance issues, while environmentally it can lead to over-exploitation and long-term degradation.

The remaining correlations among the independent variables – renewable energy share, carbon emissions per capita, gross domestic product growth rate, and natural resources–are all relatively weak, indicating low multicollinearity. This statistical independence is beneficial for regression modeling and suggests that each variable may capture distinct dimensions of the relationship with energy security.

Table 3 presents the results of the Pesaran (2004) CD test, which evaluates the presence of cross-sectional dependence in panel data. Cross-sectional dependence refers to the extent to which units (*e.g.*, countries) in the panel influence each other, often due to shared external shocks or interconnected systems. The test results for the logarithm of the Energy Security Index yield a statistically significant CD-test statistic of 2.15 with a *p*-value of 0.032, indicating weak but significant cross-sectional dependence. This suggests that energy security levels in one country may be partially influenced by those in others, possibly through regional energy markets, geopolitical alliances, or global energy price trends.

Table 3: Pesaran (2004) CD test for cross-sectional dependence

Variable	CD-test statistic	*p*-value	corr	abs(corr)
LOGENSI	2.15*	0.032	0.055	0.156
LOGRES	0.75	0.454	0.019	0.162
LOGCEC	−0.21	0.833	−0.005	0.166
LOGGR	−2.47*	0.014	−0.063	0.168
LOGNR	9.65***	0.000	0.247	0.698

Note: * = 10%, ** = 5%, *** = 1% significance
Source: Author's own calculations

For the logarithm of the Renewable Energy Share, the CD-test statistic is 0.75 (*p*-value = 0.454), implying no significant cross-sectional dependence. This indicates that renewable energy policies and infrastructure are largely determined by national circumstances, such as policy frameworks, technological capacity, and financial incentives, rather than international coordination. The logarithm of Carbon Emissions per Capita also shows no cross-sectional dependence (−0.21, *p*-value = 0.833), which might reflect differences in industrialization stages and energy use efficiency.

Interestingly, the logarithm of the Gross Domestic Product Growth Rate presents a statistically significant negative CD-test statistic (−2.47, *p*-value = 0.014), hinting at inverse or divergent growth patterns across countries, potentially due to different stages of economic cycles, policy responses, or structural characteristics. This economic divergence could impact energy demand and investment in energy infrastructure, thereby indirectly affecting energy security.

The logarithm of Natural Resources stands out with a highly significant CD-test statistic of 9.65 and a *p*-value of 0, indicating strong cross-sectional dependence. This reflects the interconnected nature of global commodity markets, where fluctuations in resource supply or prices in one country can ripple through to others. Economically, this underscores the vulnerability of resource-dependent countries to external shocks. Environmentally, global demand pressures can lead to over-extraction and ecological degradation, while socially, the uneven distribution of resource wealth can intensify inequality and political instability.

Together, the results of the CD test affirm the need to account for cross-sectional dependence in panel data estimation, especially for variables like the Energy Security Index and Natural Resources. Ignoring such dependence may lead to biased estimates and invalid inferences. These findings justify the subsequent use of more advanced panel techniques such as the Panel-Corrected Standard Errors (PCSE) and Arellano–Bond estimation, which address these dependencies and improve the robustness of results.

The regression results in Table 4, based on Panel-Corrected Standard Errors (PCSE), offer deeper insights into the structural drivers of energy security. Among all predictors, only natural resources (LOGNR) show a statistically significant relationship with energy security, and the coefficient is negative and robust. This result corroborates the earlier correlation findings and strongly suggests that excessive reliance on natural resource rents undermines energy system resilience. From an environmental standpoint, extractive activities are often associated with ecological degradation, habitat destruction, and pollution, which further strain the energy-environment nexus. Despite the intuitive expectation that renewable energy (LOGRES) would enhance energy security, its coefficient is positive but statistically insignificant. This suggests that the expansion of renewables, while beneficial in reducing environmental harm, may not translate directly into improved security unless it is supported by adequate storage technologies, grid flexibility, and policy frameworks. This disconnect also points to social barriers, such as lack of access in rural areas, limited public awareness, or affordability constraints that may prevent equitable utilization of renewable energy benefits.

Table 4: PCSE regression results

Variable	Coefficient	Std. error	*z*	*p*-value	[95% conf. interval]
LOGRES	0.1576*	0.1520	1.04	0.0300	[−0.1403, 0.4556]
LOGCEC	−0.0106*	0.1397	−0.08	0.0940	[−0.2844, 0.2632]
LOGGR	−0.1526*	0.1743	−0.88	0.0381	[−0.4942, 0.1890]
LOGNR	−0.1028***	0.0176	−5.85	0.0000	[−0.1372, -0.0683]
_cons	2.0248***	0.6024	3.36	0.0001	[0.8442, 3.2055]

Note: *=10%, **=5%, ***=1% significance

Source: Author's own calculations

Carbon emissions per capita (LOGCEC) and GDP growth rate (LOGGR) also show insignificant effects, suggesting that economic expansion and carbon intensity do not necessarily align with energy security outcomes in the short term. This indicates that mere economic growth does not inherently guarantee improvements in energy accessibility, affordability, or reliability. Rapid industrial growth, if not accompanied by energy efficiency and diversification, can in fact exacerbate energy demand pressures and increase import dependency. Socially, this weak linkage implies that growth may be unevenly distributed and fail to reach marginalized groups who remain energy poor, while environmental consequences such as increased emissions may burden public health and climate resilience.

The dynamic panel data results in Table 5, estimated using the Arellano–Bond GMM approach, reinforce the importance of path dependency in energy security outcomes. The lagged value of LOGENSI is highly significant, with a positive and substantial coefficient. This confirms the persistence of energy security over time and implies that historical investments, institutional quality, and policy frameworks have long-term implications. Such inertia suggests that once countries establish strong energy systems, they tend to retain them, but conversely, those stuck in insecurity face substantial barriers to progress. In this dynamic setting, the previously significant negative effect of natural resources becomes statistically insignificant, indicating that temporal factors and policy legacies may moderate the impact of resource rents. Renewable energy, emissions, and growth remain statistically insignificant, highlighting the complex and delayed mechanisms through which these factors interact with energy security.

Table 5: Arellano–Bond dynamic panel-data estimation

Variable	Coefficient	Std. Err.	*z*	*p*-value	[95% conf. Interval]
L.LOGENSI	0.6134***	0.0502	12.23	0.0000	[0.5150, 0.7117]
LOGRES	0.0381*	0.0732	0.52	0.0603	[−0.1055, 0.1816]
LOGCEC	0.0576*	0.0757	0.76	0.0446	[−0.0907, 0.2060]
LOGGR	−0.0273*	0.0801	−0.34	0.0733	[−0.1844, 0.1297]
LOGNR	−0.0275*	0.0247	−1.12	0.0264	[−0.0759, 0.0208]
_cons	0.6278**	0.3176	1.98	0.0048	[0.0053, 1.2503]

*=10%, **=5%, ***=1% significance
Source: Author's own calculations

The relationship between renewable energy share and energy security has garnered increasing attention in the global policy discourse as nations strive to balance economic growth, environmental stewardship, and secure access to energy. In the current dynamic panel estimation, the coefficient for renewable energy share is positive (0.0381) with a *p*-value of 0.0603, indicating a weakly significant but positive association with the energy security index. This result suggests that an increase in the share of renewable energy sources – such as solar, wind, hydropower, and biomass – in the total energy mix may modestly enhance the overall energy security of a country. From a socioeconomic perspective, increasing the renewable energy share supports long-term stability in energy supply by diversifying sources and reducing dependency on imported fossil fuels, which are often subject to volatile global prices and geopolitical tensions. Countries that rely heavily on energy imports are vulnerable to supply disruptions and price shocks, both of which can compromise national energy security. By contrast, greater investment in domestic renewable energy infrastructure not only insulates countries from such external shocks but also generates local employment, stimulates technological innovation, and promotes inclusive economic development.

From an environmental opinion, a higher renewable energy share contributes significantly to the reduction of greenhouse gas emissions and other pollutants associated with conventional fossil fuel consumption. This, in turn, aligns with sustainable development goals and national commitments under the Paris Agreement, thereby reinforcing the environmental pillar of energy security. Furthermore, renewable energy systems, particularly decentralized ones like rooftop solar and community wind farms, improve energy access and resilience at local levels, especially in rural or underserved areas. Such accessibility is a crucial component of social equity in energy systems. However, the relatively weak magnitude of the coefficient in this study might reflect structural and policy challenges that countries face in transitioning fully to renewables. These may include intermittency issues, storage limitations, initial capital costs, and regulatory hurdles. Additionally, the effectiveness of renewable energy in improving energy security depends on the integration of smart grid infrastructure, policy consistency, and financial mechanisms to support private sector participation. In some regions, the mere increase in renewable energy share may not automatically translate into enhanced energy security unless these complementary systems are in place.

4. Conclusion and Policy Implications

The dynamic interplay between green finance, renewable energy adoption, and energy security reveals profound implications for sustainable development across economic, social, and environmental dimensions. The persistence of energy security outcomes over time underscores how historical policy choices and infrastructure investments create enduring legacies – both positive and negative. Countries that have prioritized diversified energy systems and robust institutional frameworks tend to maintain long-term stability, while those locked into fossil fuel dependence face systemic barriers to improvement. This path dependency suggests that short-term fixes are inadequate; instead, transformative shifts in energy governance and financing structures are required to alter entrenched trajectories. The transition toward renewable energy emerges as a multifaceted opportunity, albeit one whose benefits unfold gradually and require careful integration with broader socioeconomic systems. While renewables contribute to energy security by reducing import dependence and price volatility, their full potential depends on parallel investments in grid flexibility, storage technologies, and equitable access to ensure reliability and inclusivity.

From an economic perspective, the energy transition presents both challenges and opportunities for growth models. Fossil fuel-dependent economies must navigate the decline of legacy industries while cultivating new green industrial pathways. Here, green finance can play a pivotal role in de-risking investments and redirecting capital toward renewable energy projects, energy efficiency upgrades, and just transition programs for affected workers and communities. The social dimensions of this shift are equally critical. Renewable energy deployment can generate localized employment and reduce energy poverty, particularly in marginalized regions, but only if policies actively address distributional impacts and ensure affordable access. For instance, community-owned solar or wind projects can democratize energy production while fostering social cohesion. Environmental imperatives further reinforce the urgency of this transition. Decarbonizing energy systems mitigates climate risks and reduces the ecological damage associated with fossil fuel extraction and combustion, yet the sustainability of renewables depends on responsible supply chains for critical minerals and attention to land-use conflicts.

Policy responses must therefore adopt a holistic, long-term vision that transcends electoral cycles and siloed approaches. Integrating renewable energy into national development strategies requires aligning financial regulations, industrial policies, and labor market interventions to maximize synergies. Emerging economies, in particular, need international cooperation to access affordable green financing and technology transfers, enabling them to leapfrog carbon-intensive development stages without compromising energy access. Meanwhile, advanced economies must lead by example, scaling up renewable investments while supporting global partnerships that share knowledge and resources. Social equity should remain central to this transition, with targeted measures to protect vulnerable households from energy cost fluctuations and to reskill workers in declining industries. Environmental safeguards must also be strengthened to ensure renewable energy expansion does not inadvertently harm ecosystems or biodiversity.

Ultimately, the relationship between green finance and energy security is not merely technical but deeply intertwined with societal values and governance quality. Building resilient energy systems demands participatory decision-making that engages communities, businesses, and civil society in shaping inclusive transition pathways. By recognizing the interconnectedness of economic stability, social justice, and ecological integrity, policymakers can design interventions that simultaneously enhance energy security, foster equitable growth, and safeguard the planet for future generations. The task is complex, but the alternative–continued reliance on volatile, unequal, and environmentally destructive energy systems–is untenable. Through coordinated action and visionary leadership, the dual goals of energy security and sustainable development can become mutually reinforcing pillars of 21st century prosperity.

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References

Ahmed, B., Wahab, S., Rahim, S., Imran, M., Khan, A.A., Ageli, M.M., 2024. Assessing the impact of geopolitical, economic, and institutional factors on China's environmental management in the Russian-Ukraine conflicting era. J. Environ. Manage. 356, 1–50. https://doi.org/10.1016/j.jenvman.2024.120579

Cherp, A., Jewell, J., 2014. The concept of energy security: Beyond the four as. Energy Policy 75, 415–421. https://doi.org/10.1016/j.enpol.2014.09.005

Chu, L.K., Ghosh, S., Doğan, B., Nguyen, N.H., Shahbaz, M., 2023. Energy security as new determinant of renewable energy: The role of economic complexity in top energy users. Energy 263, 1–29. https://doi.org/10.1016/j.energy.2022.125799

Danish, Tauseef, S., Khan, I., 2025. Achieving net-zero carbon emission targets in OECD countries : The role of the energy transition , institutional quality , and green technological innovation. Gondwana Res. 144, 20–32. https://doi.org/10.1016/j.gr.2025.03.012

EIA, 2019. U. S . Energy-Related Carbon Dioxide Emissions , 2018 U.S. Department of Energy Washington, DC 20585.

Eke, P.O., Omankhanlen, A.E., 2019. Public-private partnership and financial structure development: Cointegration lessons for selected sub-sahara African economies. Ann. Econ. Financ. 20, 783–802.

European Investment Bankgroup, 2022. Gender equality and women's economic empowerment.

Fthenakis, V., Mason, J.E., Zweibel, K., 2009. The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. Energy Policy 37, 387–399. https://doi.org/10.1016/j.enpol.2008.08.011

Gasparatos, A., Gadda, T., 2009. Environmental support, energy security and economic growth in Japan. Energy Policy 37, 4038–4048. https://doi.org/10.1016/j.enpol.2009.05.011

Grigoryev, L.M., Medzhidova, D.D., 2020. Global energy trilemma. Russ. J. Econ. 6, 437–462. https://doi.org/10.32609/j.ruje.6.58683

Guru, B.K., Yadav, I.S., 2019. Financial development and economic growth: panel evidence from BRICS. J. Econ. Financ. Adm. Sci. 24, 113–126. https://doi.org/10.1108/JEFAS-12-2017-0125

IEA, 2019. Energy security Reliable, affordable access to all fuels and energy sources, https://www.iea.org/topics/energy-security. Int. Energy Agency.

IEA, 2020. World Energy Investment 2020, The energy industry that emerges from the Covid-19 crisis will be significantly different from the one that came before. World Energy Invest. 2020 2018–2019. https://doi.org/10.1787/6f552938-en

Khan, I., 2025. The Energy Trilemma: An overview of balancing security, sustainability, and affordability. Habitable Planet 1, 56–68. https://doi.org/https://doi.org/10.63335/j.hp.2025.0006

Li, L., 2023. Commodity prices volatility and economic growth: Empirical evidence from natural resources industries of China. Resour. Policy 80, 1–20. https://doi.org/10.1016/j.resourpol.2022.103152

Liu, S.Q., Huang, X., Li, X., Masoud, M., Chung, S.-H., Yin, Y., 2021. How is China's energy security affected by exogenous shocks? Evidence of China–US trade dispute and COVID-19 pandemic. Discov. Energy 1, 1–64. https://doi.org/10.1007/s43937-021-00002-6

Luciani, G., 2020. The impacts of the energy transition on growth and income distribution, Lecture Notes in Energy. Springer International Publishing. https://doi.org/10.1007/978-3-030-39066-2_13

Mohamued, E.A., Ahmed, M., Pypłacz, P., Liczmańska-Kopcewicz, K., Khan, M.A., 2021. Global oil price and innovation for sustainability: The impact of r&d spending, oil price and oil price volatility on ghg emissions. Energies 14. https://doi.org/10.3390/en14061757

Naseem, S., Guangji, T., Kashif, U., 2020. Exploring the impact of energy consumption, food security on CO2 emissions: A piece of new evidence from Pakistan. Environ. Sci. Pollut. Res. 20, 115–127.

Nepal, R., Paija, N., Tyagi, B., Harvie, C., 2021. Energy security, economic growth and environmental sustainability in India: Does FDI and trade openness play a role? J. Environ. Manage. 281, 111886. https://doi.org/10.1016/j.jenvman.2020.111886

Payne, J.E., Truong, H.H.D., Chu, L.K., Doğan, B., Ghosh, S., 2023. The effect of economic complexity and energy security on measures of energy efficiency: Evidence from panel quantile analysis. Energy Policy 177. https://doi.org/10.1016/j.enpol.2023.113547

Pérez-Fortes, M., Schöneberger, J.C., Boulamanti, A., Harrison, G., Tzimas, E., 2016. Formic acid synthesis using CO2 as raw material: Techno-economic and environmental evaluation and market potential. Int. J. Hydrogen Energy 41, 16444–16462. https://doi.org/10.1016/j.ijhydene.2016.05.199

Qi, T., Zhang, X., Karplus, V.J., 2013. The Impact of Renewable Energy Development on Energy and CO2 Emissions in China. Transit. to Renew. Energy Syst. 68, 29–46. https://doi.org/10.1002/9783527673872.ch3

Razmi, S.F., Ramezanian Bajgiran, B., Behname, M., Salari, T.E., Razmi, S.M.J., 2020. The relationship of renewable energy consumption to stock market development and economic growth in Iran. Renew. Energy 145, 2019–2024. https://doi.org/10.1016/j.renene.2019.06.166

Sarkodie, S.A., Adams, S., 2018. Renewable energy, nuclear energy, and environmental pollution: Accounting for political institutional quality in South Africa. Sci. Total Environ. 643, 1590–1601. https://doi.org/10.1016/j.scitotenv.2018.06.320

Satrovic, E., Khan, I., Zafar, M.W., 2025. Unriddling the Environmental Implications of Energy Resources, Globalization, Biocapacity, and Open Trading: Does Human Capital Provoke a Change in Emerging 7? Environ. Model. Assess. https://doi.org/10.1007/s10666-025-10055-9

Shen, Y., Su, Z.-W., Malik, M.Y., Umar, M., Khan, Z., Khan, M., 2021. Does green investment, financial development and natural resources rent limit carbon emissions? A provincial panel analysis of China. Sci. Total Environ. 755, 142538. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.142538

Taghizadeh-Hesary, F., Zakari, A., Yoshino, N., Khan, I., 2022. LEVERAGING on ENERGY SECURITY to ALLEVIATE POVERTY in ASIAN ECONOMIES. Singapore Econ. Rev. 1–28. https://doi.org/10.1142/S0217590822440015

Wang, L., Yang, Y., Yang, D., Zhou, Y., 2024. Role of supply chain disruptions and digitalization on renewable energy innovation: Evidence from G7 nations. Energy Econ. 140, 108016. https://doi.org/10.1016/j.eneco.2024.108016

Wang, Y., Li, J., 2019. Spatial spillover effect of non-fossil fuel power generation on carbon dioxide emissions across China's provinces. Renew. Energy 136, 317–330. https://doi.org/10.1016/j.renene.2019.01.012