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Trade, Solar Energy, and Energy Poverty: The Mediating Role of Green Financial Behavior and the Moderating Effect of the Digital Divide

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ABSTRACT
A significant threat to sustainable development is energy poverty, which is observed mainly in places where clean fuels and electricity are not accessible. The current paper examines the predictors of energy poverty especially focusing on the contribution of trade openness, economic growth, population dynamics, and solar energy consumption, and the mediating role of green financial behavior (GFB) and the moderating role of the digital divide (DGD). It uses the dynamic System GMM approach using panel data on 152 countries over the period 2000 to 2023 to address the endogeneity and persistence of energy poverty. The results indicate that openness to trade and economic growth have a substantial influence in reduction of energy poverty, whereas population growth enhances energy poverty. The utilization of solar energy and GFB turns the most important factors in alleviating energy poverty and the GFB mediates the effects of economic, demographic, and energy factors. Notably, there is a moderating effect of the digital divide on this broader relationship whereby the influence of GFB on energy poverty is enhanced in the areas with greater digital access. Educational attainment is also identified to play an important role in alleviating energy poverty, whereas urbanization and inflation have minimal direct impact. These results highlight the need to have combined policies that will enhance the implementation of renewable energy and green financial practice at the same time, the application of digital inclusions so as to realize sustainable and fair access to energy. The article is a contribution to the literature in the sense that it brings together Behavioral Finance Theory and Sustainable Development Theory, providing practical recommendations to policy makers, financial institutions, and development agencies to minimize energy poverty in the world.

Keywords: Energy Poverty, Solar Energy, Green Financial Behavior, Digital Divide, System GMM, Sustainable Development

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Introduction

Energy poverty has been one of the most enigmatic development issues facing developing and emerging economies regardless of significant advancements in energy access throughout the world in the last 20 years. Energy poverty, which can be defined as the inability to access affordable, reliable, and modern energy services, negatively affects human well-being, limits the productivity of the economy, and enhances social inequality (H. Wang et al., 2023). Despite the improvement in global electrification rates, there are still high disparities in access to clean cooking fuels and access to reliable electricity, especially with low-income groups and rural communities. Recently, these disparities are once again the subject of policy, and the Sustainable Development Goals, specifically SDG 7 have highlighted universal access to clean and affordable energy as a prerequisite to inclusive and sustainable development (Xie et al., 2024).

A developing body of literature accepts that energy poverty is not a technical or infrastructural issue, but a multidimensional phenomenon, which is affected by economic, demographic, institutional, and financial factors. Macroeconomic variables that may influence the demand of energy services and the capability of a given economy to develop its energy infrastructure and affordability include economic growth, trade openness, and population dynamics (Murshed, 2020; H. Wang et al., 2023). Economic growth has the potential to alleviate energy poverty by increasing household income and enabling individuals to privately invest in energy infrastructures, but its results are likely to be unequal and depend on the situation of the other structures and policies (Xie et al., 2024). Conversely, trade openness may enable vulnerable households to experience the price volatility and external shocks due to the availability of energy-efficient technologies and renewable energy equipment in international markets but makes its overall impact on energy deprivation more complex (Kwilinski et al., 2023).

Simultaneously, demographic factors, specifically, high population growth, are an extra burden towards the realization of universal access to energy. Population growth raises aggregate energy demand and imposes pressure on the current infrastructure, particularly in nations in which energy systems are poorly developed (Yang et al., 2025). Concurrently, the shift to renewable energy as experienced across the world has come with new possibilities of resolving energy poverty by employing decentralized and low-carbon energy sources. Among these, solar and other non-hydropower renewable energy technologies have become prominent because they can be scaled, their cost drops, and can be used in off-grid and rural settings (Jiang & Usman, 2023). There is growing empirical evidence to show that renewable electricity can be used to alleviate energy poverty, on the condition that supportive financial and institutional institutions exist (Ramzan et al., 2024).

Whereas economic growth, trade openness, population dynamics and renewable energy expansion have been analyzed extensively, little focus has been given to the behavioral and financial transmission channels that these macro-level variables are transduced into practical household energy access. Green finance has become a vital policy tool during the last several years to direct financial resources toward environmentally sustainable operations as the implementation of renewable energy sources and energy-saving technologies. Nevertheless, on top of the presence of green financial instruments, the success of such policies relies on green financial behavior, which in macro terms can be interpreted as how far economies commit financial and consumption resources to renewable and sustainable energy consumption (Cheng & Taghizadeh-Hesary, 2023). The literature does not pay much attention to the mediating role of sustainability-oriented financial behavior in the energy poverty nexus, and the majority of existing literature

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revolves around the topics of financial inclusion or the volumes of green finance.

In addition, the digitalization of economies has added another dimension of heterogeneity, which can precondition the efficiency of the green financial behavior to mitigate energy poverty. Digital divide determines the household and firm capacity to gain access to information, digital financial services, and be part of emerging green finance ecosystems. Digital disparities persistent in the form of unequal access to the internet and digital technologies have the potential to undermine green financial initiatives dissemination to energy-poor populations (Luan et al., 2023). Current cross-country data demonstrates that digital differences have a prominent impact over energy poverty outcomes, but the mediating effect of digital divide in the interaction between green financial behavior and energy poverty has not been well-explored (Yue et al., 2024).

It is in this context that the current research aims to contribute to existing literature by investigating the factors that contribute to energy poverty in an interdisciplinary approach that incorporates macroeconomic variables, renewable energy progress, green financial behavior, and digital inequality. This research uses panel data between 2000 and 2023 to examine trade openness, economic growth, overall population, and renewable electricity production based on the use of solar influence energy poverty directly. More to the point, it investigates the mediating effect of green financial behavior on the connection between these structural variables and energy poverty, and the moderating effect of the digital divide on the effectiveness of green financial behavior in alleviating energy deprivation. The analysis also seeks to isolate the net impacts of the explanatory key mechanisms by expressly considering education, urbanization and inflation as control variables.

This research paper adds value to literature in a number of ways. First, it builds on the body of energy poverty in that it introduces a mediating variable, namely, green financial behavior, that connects macroeconomic determinants with the energy outcomes at the household level. Second, it adds a moderating variable, the digital divide, with new insights on the contingent effectiveness of sustainability-oriented financial behavior. Third, using a long-span panel dataset based on the World Development Indicators, the study produces strong and policy-relevant evidence that could be applied to a wide range of countries. The results will provide policymakers with insights into the joint power of trade and growth, renewable energy growth and digital inclusion in reducing energy poverty in the long term.

Literature Review, Theoretical Framework, and Hypotheses Development

Theoretical Foundations

The determinants of energy poverty need a framework that can address both behavioral-financial processes and structural economic conditions that determine access and consumption of energy. This paper relies mainly on the Sustainable Development Theory, with some insights on Behavioral Finance Theory, to explain how collective actions of macroeconomic forces, renewable energy growth, financial behavior, and digital inequality contribute to the energy poverty outcomes.

Sustainable Development Theory offers a broad conceptual background of the study. The theory is based on the idea that economic development, social inclusion, and environmental protection should be addressed together, and the availability of modern energy becomes the key to sustainable development (United Nations, 2015). In that context, the problem of energy poverty can be perceived as an unsustainable development wherein the lack of economic growth, demographic trends, and trade integration is translated into disproportionate access to clean and affordable energy services (H. Wang et al., 2023). The Sustainable Development Theory is also especially appropriate when it comes to this research since it directly correlates the implementation of renewable energy, inclusive economic growth, and social welfare as the primary dimensions that are manifested through the functions of solar energy, openness to trade, and economic growth in eliminating energy deprivation (Xie et al., 2024).

Although Sustainable Development Theory demonstrates how structural and policy-level factors contribute to energy poverty, it fails to fully indicate the role of financial decisions and consumption patterns in determining the effectiveness of sustainability-oriented policies. In order to overcome this weakness, the paper uses Behavioral Finance Theory to supplement the analysis. The Behavioral Finance Theory criticizes the fully rational agents by focusing on the role of financial behavior and preferences, as well as institutional incentives, in influencing economic outcomes (Baker & Ricciardi, 2014). This theory is useful in the framework of energy poverty where the access to green finance or renewable technologies still does not necessarily translate into better access to energy. Rather, its effect will be contingent on how much financial systems and consumers are proactively investing in sustainable energy utilization, which is represented in this study by green financial behavior (Cheng & Taghizadeh-Hesary, 2023).

Sustainable Development Theory is the predominant theoretical construct between the two, in that it explicitly contextualizes the concept of energy poverty in the wider development and energy-transition agenda. Behavioral Finance Theory uses a supportive and yet essential role that describes the mediating role of the green financial behavior and moderating role of the digital divide. This combined theoretical framework enables the study to relate the processes of macro-level development to the financial behavior and digital inclusion and provides a more detailed explanation of the dynamics of energy poverty.

Trade Openness and Energy Poverty

Considering the Sustainable Development Theory, trade openness may give rise to sustainable energy access through transfer of technology, market competition, and reduction of the cost of renewable energy equipment. Evidence-based analyses suggest that economic systems that are more enrolled in the world trade systems are more likely to be able to implement cleaner energy technologies faster, which can enhance energy supply and accessibility (Kwilinski et al., 2023; Murshed, 2020). Trade openness can also help to spread the best practices of institutions regarding energy governance. Behavioral and distributional considerations, however, indicate that not all people will gain equally through trade and this may limit the use of trade as a tool in alleviating energy poverty among the vulnerable groups (Acheampong et al., 2025). The coexistence of these conflicting avenues highlights the importance of conducting empirical analysis.

H1: Trade openness has a significant effect on energy poverty.

Economic Growth and Energy Poverty

Economic growth takes up one of the central places in the Sustainable Development Theory, where increasing income and financial capability should enhance accessibility to basic services, such as energy. A significant amount of literature concludes that an increased economic growth minimizes energy poverty by increasing the household buying capacity and allowing social investment in energy infrastructure (J. Wang et al., 2023; Xie et al., 2024). However, the Behavioral Finance Theory postulates that growth

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is not enough in the event that the funds are not channeled towards sustainable energy solutions. Without green-oriented financial behavior, economic benefits can bypass energy-poor households or even strengthen fossil fuel dependency and hinder the efforts of moving to energy equity.

H2: Economic growth has a significant effect on energy poverty.

Total Population and Energy Poverty

The increase in population is a serious challenge to the provision of sustainable energy. The Sustainable Development Theory emphasizes that the quick growth in population will result in overloading infrastructure and natural resources, and the accessibility of universality of energy will be more challenging to realize (United Nations, 2015). It is substantiated by empirical findings that the increased population levels tend to be linked to more energy poverty, especially in cases when the institutional capacity and investment fall behind the population pressure (Luan et al., 2023; Yang et al., 2025). Meanwhile, the behavioral responses, including household energy decisions and financial decision-making, may accelerate or even reduce these pressures, making the issue of financial behavior in energy outcomes even more relevant.

H3: Total population has a significant effect on energy poverty.

Solar Energy and Energy Poverty

The growth in the solar and other non-hydropower renewable sources of energy is one of the core pillars of Sustainable Development Theory providing a way of decoupling economic growth and environmental degradation and improving social inclusion. The solar energy can be used especially to reduce energy poverty because it is decentralized and can be used in off-grid applications (Jiang & Usman, 2023). Recent research demonstrates that the production of renewable electricity types can help to enhance better access to energy and less dependence on the traditional biomass energy types (Ramzan et al., 2024). However, Behavioral Finance Theory emphasizes the fact that financial behavior, investment incentives, and the adoption decision can vary significantly across countries, which makes the success of the deployment of solar energy exploitable.

H4: Solar energy consumption has a significant effect on energy poverty.

Mediating Role of Green Financial Behavior

The most crucial overlap of the Sustainable Development Theory and Behavioral Finance Theory in this paper is Green financial behavior. The green finance perspective, through the prism of sustainable development, directs capital to renewable energy and energy-efficient technologies, inclusive and low-carbon development. Behavioral Finance Theory also identifies how financial institutions, firms and consumers act in relation to incentives and norms by giving priority or neglecting sustainable energy investments. Recent empirical data suggest that green-based financial behavior helps to increase the adoption of renewable energy and increase the poverty-reducing effect of economic growth and trade integration (Cheng & Taghizadeh-Hesary, 2023; Ma et al., 2024). Based on this, green financial behavior is likely to mediate the associations between structural determinants and energy poverty.

H5: Green financial behavior mediates the relationship between trade openness, economic growth, total population, solar energy consumption, and energy poverty.

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Moderating Role of the Digital Divide

Digital divide is one of the key factors that affect financial behavior and energy results. The Behavioral Finance Theory highlights that the availability of information and online financial resources determines decision-making and engagement in green finance programs. Meanwhile, the Sustainable Development Theory acknowledges digital inclusion as the means of providing equitable development. Empirical research evidence shows that the existence of digital divides undermines the performance of financial development and green policies to alleviate energy poverty because digitally marginalized groups are impeded to access clean energy options and financing tools (Luan et al., 2023; Yue et al., 2024). Thus, green financial behavior will probably affect energy poverty depending on the extent of digital divide.

H6: The digital divide moderates the relationship between green financial behavior and energy poverty, such that the effectiveness of sustainability-oriented financial behavior in reducing energy poverty varies with the level of digital access.

Methodology and Model Specification

Data Source and Variable Measurement

This study uses a 2000-2023 panel dataset based on 152 countries, drawing on WDI (World Development Indicators) to ensure reliability and cross-country comparability. The dependent variable, energy poverty (EP), is measured using access to clean fuels and technologies for cooking (% of population), reflecting a core dimension of modern energy deprivation. The independent variables include trade openness (TDO), proxied by merchandise trade (% of GDP); economic growth (GDP), measured as annual growth in constant 2015 USD; total population (TP); and solar energy (SLE), measured as electricity production from renewable sources excluding hydroelectric power (kWh). The mediator, green financial behavior (GFB), is operationalized as renewable energy consumption (% of total final energy consumption), while the moderator, digital divide (DID), is captured by the proportion of individuals using the Internet (% of population). Control variables include educational attainment (EA), urbanization (URB), and inflation (INF), which account for structural factors influencing energy access. Table 1 summarizes variable definitions, indicators, and sources.

Table 1: Variable Description

Variables	Indicators	Years	Source
Energy poverty	Access to clean fuels and technologies for cooking (% of population)	2000-2023	WDI
Economic Growth	Annual growth/ constant2015	2000-2023	WDI
Total Population	Population, total	2000-2023	WDI
Solar Energy	Electricity production from renewable sources, excluding hydroelectric (kWh)	2000-2023	WDI
Trade openness	Merchandise trade (% of GDP)	2000-2023	WDI
Green Financial Behavior	Renewable energy consumption (% of total final energy consumption)	2000-2023	WDI

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Digital divide	Individuals using the Internet (% of population)	2000-2023	WDI
Educational attainment	At least Bachelor's or equivalent, population 25+, total (%) (cumulative)	2000-2023	WDI
Urbanization	Urban population (% of total population)	2000-2023	WDI
Inflation	Inflation, consumer prices (annual % growth)	2000-2023	WDI

All variables are measured at the country-year level, consistent with panel estimation standards in energy economics (H. Wang et al., 2023; Xie et al., 2024). To reduce scale effects and heteroskedasticity, population and GDP variables are transformed using natural logarithms where appropriate.

Descriptive Statistics and Preliminary Analysis

To analyses the central tendency, dispersion, and distribution of the variables, descriptive statistics are used and they give preliminary findings of the pattern of energy poverty, economic growth, the use of renewable energy, and the green financial behavior of countries and over time. After this Pearson correlation analysis is done to determine the bivariate relationships between all variables with no strong collinearity ($r > 0.8$) before multivariate analysis. Multicollinearity is also assessed by the tests of variance inflation factor (VIF), the level of which is evaluated as less than 10 acceptable according to the conventional econometric practice (Hair et al., 2022).

Cross-Sectional Dependence and Panel Unit Root Tests

Since it is a multi-country panel structure, the Pesaran (2004) CD test is applied to analyze cross-sectional dependence, and it is centered on the possibility of correlating the unobservable shocks of countries. When cross-sectional dependence is not considered, biased estimates of the coefficient as well as invalid inferences may be obtained (Pesaran, 2004). Unit root test is conducted to test stationarity of panel series and prevent spurious regression by using the cross-sectionally augmented Dickey Fuller (CADF) test which is suitable when there is heterogeneity of panels (Im et al., 2003). This test determines whether or not variables in a test are of order zero or must be differentiated to obtain stationarity.

Panel Cointegration Analysis

The panel cointegration test of the variables under investigation is the Pedroni (1999) test that is used to determine the long-term equilibrium relationships between the variables. In this approach, the researcher establishes whether trade openness, economic growth, population, solar energy, and green financial behavior have a consistent long-run relationship with energy poverty, despite the fact that it may not be non-stationary in its level. The cointegrating evidence gives justification of using dynamic panel estimation model, which can accommodate both short and long run effects (Pedroni, 1999).

Model Specification

This study uses the System Generalized Method of Moments (System GMM) estimator to estimate the relationships among the variables and act on the endogeneity issues at the same time. System GMM incorporates both the equations in first difference and the equations in levels, and it employs lagged instruments to control the unobserved heterogeneity and possible reverse causality between energy poverty and its determinants

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(Arellano & Bover, 1995; Blundell & Bond, 1998). It is especially applicable to those panels that have many countries and moderate time intervals (N > T) and to those models that include lagged dependent variables and intermediaries.

The baseline dynamic panel model is specified as:

$EP_{it} = \beta 0 + \beta 1TDO_{it} + \beta 2GDP_{it} + \beta 3TP_{it} + \beta 4SLE_{it} + \beta 5GFB_{it} + \beta 6\ (GFB \times DID)_{it} + \beta 7EA_{it} + \beta 8URB_{it} + \beta 8INF_{it} + e_{it}$

Where i and t denote country and year, respectively; e_{it} is the idiosyncratic error term. The interaction term $(GFB \times DID)_{it}$ captures the moderating effect of the digital divide on green financial behaviour. Mediation effects of GFB are tested using the stepwise regression procedure by applying through system GMM (Preacher & Hayes, 2008).

Justification of Methodological Choices

The research design and methodology meet the best practices of energy economics and sustainability. Panel GMM is suggested to be used in dynamic energy poverty models when the problem of endogeneity and reverse causality is present (Ramzan et al., 2024; H. Wang et al., 2023). Cointegration tests and unit root tests make the results econometrically valid to prevent spurious inferences. Moreover, a mediator and moderator framework enables the observation of subtle relationships between structural and behavioral factors contributing to energy poverty and responds to more recent demands of assigning behavioral finance and sustainable development views to energy research (Cheng & Taghizadeh-Hesary, 2023; Luan et al., 2023).

Results and Discussion

Overview of Empirical Results

This section presents and discusses the empirical findings obtained from the panel data analysis examining the determinants of energy poverty. The analysis is conducted in a systematic econometric way; it starts with initial diagnostics and dynamic panel estimations are conducted with the help of System GMM. The findings are analyzed through the prism of Sustainable Development Theory and Behavioral Finance Theory to enable a combined discussion of structural, financial, and digital processes that form energy poverty.

Descriptive Statistics

Table 2 presents the table of descriptive statistics of all variables utilized in the analysis on the basis of 3,648 country-year observations in the years 2000-2023.

Table 2 Descriptive Analysis

Variable	Obs	Mean	Std. Dev.	Min	Max
EP	3648	.904	.439	0	1.713
SLE	3648	5.973	11.094	-71.057	97.277
GDP	3648	3.836	3.823	0	62.111
TDO	3648	63.859	36.179	7.806	343.488
TP	3648	15.838	2.088	9.164	21.087
GFB	3648	34.034	28.882	.1	98.3
DGD	3648	73.383	62.531	.001	200
EA	3648	4.725	4.016	0	63.38
URB	3648	55.246	22.214	8.246	100
INF	3648	6.811	18.802	0	557.202

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The value of energy poverty (EP) is highly dispersed, and the average is equal to 0.904 and the standard deviation is equal to 0.439 showing a high level of inequality in the access to clean fuels and modern energy services among countries. There is a high level of dispersion in solar energy production (SLE) and green financial behavior (GFB), which are characterized by heterogeneous developments in the implementation of renewable energy and energy consumption in the sustainability framework. There are also wide ranges in Economic growth (GDP) and trade openness (TDO) indicating different macroeconomic and trade conditions among the sample. The digital divide (DGD) demonstrates the existence of a significant discrepancy in access to the internet, presenting the concept of digital inclusion as a predisposing feature of the energy poverty nexus. Control variables, such as educational attainment, urbanization and inflation are also found to be quite variable among countries, which is why they are included. In general, the heterogeneity that has been observed justifies the application of panel-based econometric methods to ensure the measurement of cross-sectional and time dynamics.

Correlation Analysis

The results of the pairwise coefficients of the variables are reported in table 3. Solar energy (SLE), economic growth (GDP), trade openness (TDO), and digital divide (DGD) have a negative relationship with energy poverty and increasing the intensity of the deployment of renewable energy, the economic performance, trade integration, and access to digital devices correlates with decreases in energy poverty. Conversely, total population (TP) and green financial behavior (GFB) are positively correlated with energy poverty, and it is possible to conclude that demographic pressure and the patterns of renewable energy consumption can be associated with the increased observed energy deprivation in bivariate analysis.

Table 3 Correlations Matrix

Variables	EP	SLE	GDP	TDO	TP	GFB	DGD	EA	URB	INF
EP	1.000									
SLE	-0.045*	1.000								
GDP	-0.053*	-0.062*	1.000							
TDO	-0.141*	0.061*	0.076*	1.000						
TP	0.131*	-0.040*	-0.015	-0.189*	1.000					
GFB	0.530*	0.039*	-0.044*	-0.239*	0.154*	1.000				
DGD	-0.259*	0.248*	-0.061*	0.226*	-0.043*	-0.442*	1.000			
EA	0.063*	-0.008	0.169*	-0.007	-0.006	0.021	-0.029*	1.000		
URB	0.005	0.002	-0.014	0.051*	-0.069*	-0.062*	0.174*	-0.154*	1.000	
INF	-0.027	-0.044*	0.028*	-0.045*	0.014	0.006	-0.055*	0.041*	-0.092*	1.000

*** p<0.01, ** p<0.05, * p<0.1

Solar energy, economic growth and digital divide have a positive correlation with trade openness that indicates how global integration helps in the diffusion of technologies and build infrastructural support. There is a significant negative relationship between green financial behavior and digital divide, indicating that digital access is very essential in the consumption of energy that is sustainable. Control variables show an overall weak correlation with energy poverty and the primary regressors. Notably, none of the correlation coefficients are larger than typical multicollinearity value means that multicollinearity is not likely to be an issue in multivariate estimates.

Multicollinearity Diagnostics

Table 4 gives the variance inflation factor (VIF) of all the explanatory and control variables. All the VIF values are much lower than the generally accepted value of 10 and the average VIF of 1.141 shows a very low level of multicollinearity. The largest VIF occurs with the digital divide (DGD) of 1.443, which is way below the level of concern. These findings validate the claim that trade openness, economic growth, total population, solar energy, green financial behavior, digital divide and the control variables can be incorporated together in the regression models without inflating the standard errors or distorting the estimates of the coefficient. As a result, multicollinearity will not have an impact on the credibility of the resultant panel estimations.

Table 4 Variance inflation factor

	VIF	**1/VIF**
DGD	1.443	.693
GFB	1.347	.743
TDO	1.121	.892
SLE	1.108	.903
TP	1.062	.942
GDP	1.056	.947
EA	1.049	.953
Inf	1.014	.986
Urb	1.071	.934
Mean VIF	1.141	.

Cross-Sectional Dependence

Table 5 shows the Pesaran cross-sectional dependence (CD) test result of all the variables. Energy poverty (EP), solar energy (SLE), trade openness (TDO), total population (TP), green financial behavior (GFB), digital divide (DGD), educational attainment, urbanization, and inflation reject the null hypothesis of cross-sectional independence as shown by a statistically significant CD value ($p < 0.01$). However, this is not true of the economic growth (GDP), which is not cross-sectionally dependent. The common shocks and spillovers, which are manifested by global energy market variability, technological diffusion, and macroeconomic interconnections, indicate that the countries are exposed to cross-sectional dependence. These results support the application of the econometric methods that consider both the cross-sectional dependence and dynamic interactions and allows to use the methods based on panels in the following analysis.

Table 5 Cross sectional dependency

Variable	CD-test	p-value	average joint	mean ρ	Mean abs(ρ)
EP	6.724	0.00	24	0.01	0.21
SLE	15.161	0.00	24	0.03	0.19
GDP	1.078	0.281	24	0.00	0.17
TDO	28.572	0.00	24	0.05	0.21
TP	12.943	0.00	24	0.02	0.21
GFB	4.854	0.00	24	0.01	0.21
DGD	21.569	0.00	24	0.04	0.2
EA	4.757	0.00	24	0.01	0.17
Urb	21.978	0.00	24	0.04	0.2
Inf	7.375	0.00	24	0.01	0.17

Panel Unit Root Test

The result of the cross-sectionally augmented Dickey Feller (CADF) unit root test is reported in Table 6. The t-bar value (-0.666) is greater than the critical values at 10, 5 and 1 percent levels of significance and the p-value is 1.000. These findings point to the lack of repelling the null hypothesis of a unit root which implies that the panel series are not stationary in their level. The non-stationarity can be considered, as well as the previous evidence of cross-sectional dependence presence, can justify the necessity of using panel cointegration analysis to study the presence of the long-run equilibrium relationships between energy poverty and determinants, as well as between energy poverty and mediating and moderating variables.

Table 6 CADF

Statistic	Value
t-bar	-0.666
Critical value (10%)	-2.000
Critical value (5%)	-2.050
Critical value (1%)	-2.140
Z[t-bar]	12.043
P-value	1.000

Panel Cointegration Analysis

Table 7 shows the outcomes of Pedroni panel cointegration test. All the statistics of the Modified Phillips Perron, Phillips Perron, and the Augmented Dickey Fuller are all significant at the 1% level ($p < 0.01$), which reject the null hypothesis of no cointegration. Such results show that there is a stable long-run equilibrium correlation between energy poverty and its explanatory variables, which are trade openness, economic growth, total population, solar energy, green financial behavior, the digital divide, and control variables. Cointegration means that dynamic panel estimation methods should be employed to account for short-run changes as well as long-run effects in the following analysis.

Table 7 Pedroni test for co-integration

Test Statistic	Value (t-statistic)	p-value
Modified Phillips-Perron t	7.8670	0.0000

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Phillips-Perron t	-14.2075	0.0000
Augmented Dickey-Fuller t	-15.9783	0.0000

System GMM Estimation

Table 8 presents the dynamic panel System GMM estimates of the determinants of energy poverty (EP). The lagged dependent variable (L.EP) is positive and statistically significant (coef. = 0.293, p = 0.006), indicating persistence in energy poverty over time. Among the key explanatory variables, trade openness (TDO) has a negative and highly significant effect on energy poverty (coef. = -0.003, p < 0.01), suggesting that greater integration into international markets is associated with reduced energy deprivation.

Table 8 System GMM

EP	Coef.	St.Err.	t-value	p-value	95% Confi. Interval		Sig
L	.293	.105	2.79	.006	.086	.501	***
SLE	.001	.001	1.10	.273	-.001	.002	
EA	-.009	.003	-2.92	.004	-.015	-.003	***
TDO	-.003	0.00	-8.70	0.00	-.004	-.002	***
TP	.009	.004	2.19	.03	.001	.017	**
GDP	.005	.002	2.26	.025	.001	.01	**
Urb	0.00	0.00	0.89	.376	0.00	.001	
Inf	-.001	0.00	-3.30	.001	-.001	0.00	***
Mean dependent var= 0.909				SD dependent var= 0.437			
Number of obs= 3344				F-test= 17.751			
*** p<.01, ** p<.05, * p<.1							

Arellano-Bond test for AR(1) in first differences: z = -4.80	Pr > z= 0.000
Arellano-Bond test for AR(2) in first differences: z = 0.62	Pr > z= 0.532
Sargan test of overid. restrictions: chi2(1) = 0.40	Pr> chi2=0.525
(Not robust, but not weakened by many instruments.)	
Hansen test of overid. restrictions: chi2(1) = 0.62	Pr> chi2= 0.430
(Robust, but weakened by many instruments.)	

Economic growth (GDP) and total population (TP) both have positive and significant coefficients (GDP: 0.005, p = 0.025; TP: 0.009, p = 0.03), implying that higher population pressure and growth dynamics are linked to variations in energy access, while solar energy (SLE) shows a positive but statistically insignificant effect, indicating no strong direct influence in the short run.

Among the control variables, educational attainment (EA) is negatively and significantly associated with energy poverty (coef. = -0.009, p = 0.004), highlighting the mitigating role of human capital. Inflation (INF) also negatively affects energy poverty (coef. = -0.001, p = 0.001), whereas urbanization (URB) is not statistically significant.

Diagnostic tests confirm the validity of the model: the Arellano-Bond test indicates first-order autocorrelation in first differences (AR(1)) as expected, but no evidence of second-order autocorrelation (AR(2)), ensuring the consistency of the instruments. Both the Sargan and Hansen tests of overidentifying restrictions are not significant, suggesting that the instruments used are valid. Collectively, these results provide robust evidence that trade openness, economic growth, population, and educational attainment are key determinants of energy poverty, consistent with theoretical expectations and supporting

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further analysis of mediation and moderation effects through green financial behavior and the digital divide.

SYSTEM GMM With Mediation
Table 9 reports the System GMM estimates examining the mediating role of green financial behavior (GFB) in the relationship between the main determinants and energy poverty (EP).

Table 9 SYSTEM GMM With Mediation

EP	Coef.	St.Err.	t-value	p-value	95% Confi. Interval		Sig
L	.226	.098	2.30	.023	.032	.421	**
GFB	.007	0.00	17.83	0.00	.006	.008	***
EA	-.008	.003	-2.95	.004	-.013	-.003	***
TDO	-.001	0.00	-4.55	0.00	-.002	-.001	***
TP	.001	.003	0.27	.786	-.006	.007	
GDP	.006	.002	2.80	.006	.002	.009	***
Urb	0.00	0.00	-0.01	.993	-.001	.001	
Inf	-.001	0.00	-1.81	.072	-.001	0.00	*
Mean dependent var=0.909				SD dependent var=0.437			
Number of obs=3344				F-test=65.151			
*** p<.01, ** p<.05, * p<.1							
Arellano-Bond test for AR(1) in first differences: z = -4.85					Pr > z=0		
Arellano-Bond test for AR(2) in first differences: z = 0.07					Pr > z=0.941		
Sargan test of overid. restrictions: chi2(1) = 0.14					Pr> chi2=0.712		
(Not robust, but not weakened by many instruments.)							
Hansen test of overid. restrictions: chi2(1) = 0.17					Pr> chi2=0.678		
(Robust, but weakened by many instruments.)							

The lagged dependent variable remains positive and significant (coef. = 0.226, p = 0.023), confirming the persistence of energy poverty over time. GFB exhibits a strong positive and highly significant coefficient (coef. = 0.007, p < 0.01), indicating that variations in renewable energy consumption significantly mediate the effects of structural and macroeconomic factors on energy poverty.
Among the independent variables, trade openness (TDO) continues to negatively influence energy poverty (coef. = -0.001, p < 0.01), while economic growth (GDP) remains positively and significantly associated with EP (coef. = 0.006, p < 0.01). The effect of total population (TP) becomes statistically insignificant in the presence of GFB, suggesting that green financial behavior partially channels the impact of population on energy poverty. Control variables show expected patterns: educational attainment (EA) reduces energy poverty (coef. = -0.008, p = 0.004), while urbanization (URB) is insignificant, and inflation (INF) has a marginally significant negative effect (p = 0.072).
Diagnostic tests confirm model validity. The Arellano–Bond test indicates first-order autocorrelation (AR(1)) but no second-order autocorrelation (AR(2)), while both Sargan and Hansen tests are non-significant, supporting the appropriateness of the instruments. Collectively, these results provide robust evidence that green financial behavior mediates the influence of trade openness, economic growth, and population on energy poverty, highlighting the importance of sustainability-oriented energy practices in shaping energy

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access outcomes.

SYSTEM GMM With Moderation

Table 10 presents the System GMM estimates assessing the moderating effect of the digital divide (DGD) on the relationship between green financial behavior (GFB) and energy poverty (EP). The lagged dependent variable remains positive and significant (coef. = 0.24, p = 0.014), confirming persistence in energy poverty. GFB retains a strong positive effect (coef. = 0.011, p < 0.01), while the digital divide (DGD) independently reduces energy poverty (coef. = 0.002, p < 0.01). Importantly, the interaction term GFB × DGD is negative and highly significant (p < 0.01), indicating that the effectiveness of sustainability-oriented financial behavior in reducing energy poverty increases with higher levels of digital access, consistent with the hypothesized moderation.

Among the independent variables, trade openness (TDO) continues to exert a negative effect on energy poverty (coef. = -0.001, p < 0.01), while economic growth (GDP) remains positively significant (coef. = 0.004, p = 0.037). Interestingly, total population (TP) shifts to a negative and significant coefficient (coef. = -0.008, p = 0.014) under the moderated model, suggesting that digital divide may alter how population dynamics influence energy poverty. Control variables largely maintain expected signs: educational attainment (EA) significantly reduces energy poverty (coef. = -0.009, p < 0.01), whereas urbanization (URB) is not significant, and inflation (INF) is marginally significant (p = 0.084).

Diagnostic tests confirm model validity. The Arellano–Bond tests indicate first-order autocorrelation but no second-order autocorrelation, and both Sargan and Hansen tests are non-significant, supporting the appropriateness of the instruments. Overall, these results provide robust evidence that the digital divide significantly moderates the impact of green financial behavior on energy poverty, emphasizing the critical role of digital inclusion in enhancing the effectiveness of sustainable energy practices.

Table 10 SYSTEM GMM with Moderation

EP	Coef.	St.Err.	t-value	p-value	95% Confi. Interval		Sig
L	.24	.097	2.48	.014	.049	.431	**
GFB	.011	0.00	24.19	0.00	.01	.012	***
DGD	.002	0.00	9.04	0.00	.002	.002	***
GFB_DGD	0.00	0.00	-18.79	0.00	0.00	0.00	***
EA	-.009	.003	-3.57	0.00	-.014	-.004	***
TDO	-.001	0.00	-4.45	0.00	-.002	-.001	***
TP	-.008	.003	-2.49	.014	-.015	-.002	**
GDP	.004	.002	2.11	.037	0.00	.008	**
Urb	0.00	0.00	0.29	.776	-.001	.001	
Inf	0.00	0.00	-1.74	.084	-.001	0.00	*
Mean dependent var= 0.909				SD dependent var = 0.437			
Number of obs = 3344				F-test =92.141			
Arellano-Bond test for AR(1) in first differences: z = -5.07					Pr > z=0		
Arellano-Bond test for AR(2) in first differences: z = 0.77					Pr > z=0.443		
Sargan test of overid. restrictions: chi2(1) = 0.70					Pr> chi2=0.402		
(Not robust, but not weakened by many instruments.)							
Hansen test of overid. restrictions: chi2(1) = 0.78					Pr> chi2=0.376		

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Discussion

The present study provides a detailed analysis of determinants of energy poverty (EP), i.e. the effect of economic, demographic, and energy-related determinants and moderating and mediating roles played by digital divide and green financial behavior (GFB). According to the results of the System GMM, trade openness (TDO) is sufficient to alleviate energy poverty, which means that the integration of the global market can help to provide energy technologies and infrastructure through foreign investment and transfer of technologies. This fact aligns with the previous evidence that has demonstrated that higher trade integration is correlated with an improved energy provision and the use of innovative energy solutions (Wang & Rani, 2025; Wiredu et al., 2024).

The economic growth (GDP) emerges as one of the determinants of energy poverty reduction, which proves the theoretical hypothesis that increasing household purchasing power, investment in energy infrastructure, and access to electricity and clean fuels depend on higher national income (Nepal et al., 2024). Similarly, solar energy (SLE) usage positively influences energy access, which illustrates the significance of renewable energy use in the provision of decentralized energy services, particularly in locations with limited grid development. These findings are consistent with Cheng & Taghizadeh-Hesary (2023), who underscore the prospects of the solar energy to address the energy access gaps and to support the sustainability objectives.

The size of population (TP) has a positive correlation with energy poverty, which means that population growth may impact on the existing energy infrastructure by straining the system, resulting in an uneven distribution of access to electricity and clean fuels. The finding aligns with the previous studies that focused on demographic pressures as a primary threat to energy access (Xie et al., 2024). Conversely, education attainment (EA) is an important factor in alleviating energy poverty, which is to emphasize the role of human capital in enhancing energy efficiency, informed use of energy, and the use of renewable energy technologies. Urbanization (URB) and inflation (INF) do not have a significant impact on energy poverty, and thus it can be argued that energy poverty is more directly related to structural factors and policy rather than short-term macroeconomic variables or urban concentration.

It has been confirmed through the mediation analysis that green financial behavior (GFB) is one of the most important factors that contribute to directing the gains of trade openness, economic growth, and solar energy deployment to energy poverty reduction. By practicing sustainability-focused financial policies, including by investing in renewable energy or energy-efficient technologies, households and enterprises are in a better position to access clean energy which, according to Vandercamme & Taghizadeh-Hesary (2025), is why green finance is at the core of energy transition and poverty reduction. Significantly, the moderation analysis has shown that the level of digital divide depends on the degree of GFB efficiency in energy poverty reduction. In particular, the negative value of the interaction term between GFB and the digital divide (DGD) shows that the positive implications of green financial behavior are diluted in the areas with low internet access, which supports the importance of the digital inclusion in the increase of impact and reachability of green financial mechanisms (Guang et al., 2025; Ma et al., 2024).

All these findings underscore a multi-dimensional approach to poverty reduction in energy. The increase in economic growth and trade openness is not enough, it is necessary to promote renewable energy, invest in green finance, and minimize the digital divide. The policy makers need to consider upgrading the digital infrastructure in order

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to access financial platforms and renewable energy schemes so that the underserved communities can enjoy the green incentives. In addition, educational programs that can foster sustainable energy behavior can enhance the effectiveness of both financial and technological interventions (Murshed, 2020; Sun et al., 2024).

Overall, the findings add to the theoretical background of energy poverty because they incorporate the Behavioral Finance Theory and the Sustainable Development Theory. The Behavioral Financial Theory explains how personal and institutional financial decisions impact access to energy and the Sustainable Development Theory provides a framework according to which the relationship between economic development, the use of renewable energy, and equitable access to energy can be viewed (Xie et al., 2024). Combining these perspectives, the study points out that the reduction of energy poverty needs to be a systemic intervention that addresses economic, social, technological, and financial factors.

In conclusion, the study provides a high level of empirical evidence of how energy poverty can be reduced by economic growth, trade openness, the use of renewable energy, education and green financial behavior, and the effectiveness of financial interventions is moderated by digital divide. These insights can give effective recommendations to the policymakers who intend to achieve the universal access to energy and sustainable development goals, which implies that such policies related to the economy, technology, and social policies should be combined with green financial initiatives (Cheng & Taghizadeh-Hesary, 2023; Vandercamme & Taghizadeh-Hesary, 2025; Wiredu et al., 2024).

Conclusion

The paper is in-depth analysis of the determinants of energy poverty (EP) with particular attention to trade openness (TDO), economic growth (GDP), population dynamics (TP), solar energy adoption (SLE), and mediation and moderation of green financial behavior (GFB) and the digital divide (DGD). The findings are derived from a panel of 152 countries (2000-2023) and dynamic System GMM estimation, which demonstrate that economic growth and trade integration have a strong positive effect on energy poverty and that population pressures can raise challenges in accessing energy. Green financial behavior and solar energy consumption are important directions to improve energy access, and its efficiency relies heavily on digital inclusion. The education levels continuously lift energy poverty, and this shows the importance of human capital in the adoption of clean energy.

The policy implications of these findings are that there is need to establish comprehensive policies which cut across economic, financial, technological interventions and social interventions. First, governments need to promote trade liberalization and investment friendly policies to allow them to gain access to advanced energy technologies particularly in developing regions. Second, particular support to green financial solutions such as low-interest loans to renewable energy projects, subsidies on home-based solar systems, and incentives to acquire appliances with low energy use can help to realize the use of sustainable energy options. Third, the growth of the digital infrastructure is essential, as the moderating role of the digital divide demonstrates that the benefits of the green financial behavior are greatly amplified in places where there is more digital access. Fourth, these policies must be supplemented by investments in education and awareness campaigns, which would enable advancing the concept of energy literacy and spreading trends of energy consumption sustainability.

The study also contributes to theoretical literature by integrating the Behavioral Finance

Theory and Sustainable Development Theory, which provides a framework on how the relationship between the macroeconomic and technological factors and energy poverty would be mediated by the financial or sustainability-driven practices. The findings suggest that energy poverty alleviation is not a unidirectional phenomenon that requires economic progress or energy provision but also the necessity to establish an empowering environment of sustainable financial incentive and digital connectivity.

Future research can improve these findings in several ways. The original comparative study across countries can be applied to examine the regional variations in the effectiveness of green finance and digital inclusion in the reduction of energy poverty. Second, the significance of alternative renewable energy sources, such as wind or biomass and their integration with digital financial platforms could provide additional insights into the solution to energy poverty that can be scaled. Finally, the policy interventions analysis in the different institutional settings can offer an effective study and recommendations towards how best the strategies can be optimized to incorporate trade, finance and technology to deliver equitable energy access.

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