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ENERGY POVERTY, INSTITUTIONAL QUALITY, AND ENVIRONMENTAL DEGRADATION IN PAKISTAN: A TIME SERIES EMPIRICAL ANALYSIS

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ABSTRACT: Pakistan, as a developing country, faces an energy crisis that encourages the use of traditional energy sources at both the household and industrial levels. Pakistan aims to achieve the SDG target (2030) as per the UN SDG target. This study aims to examine the impact of energy poverty, poverty, income inequality, energy consumption, foreign direct investment (FDI) inflows, economic growth, institutional quality, and energy prices on environmental degradation in Pakistan, and verify the validity of the Environmental Kuznets Curve (EKC) hypothesis and the pollution haven hypothesis. A dynamic ARDL simulation model is used to predict the impact of independent (Positive and negative shocks) variables on the dependent variable through graphs. The findings of the dynamic ARDL simulation model reveal that energy poverty, globalisation, poverty, economic growth, FDI inflows, and income inequality in Pakistan increase environmental degradation, while the consumption of renewable energy and institutional quality help to reduce environmental degradation. Furthermore, the EKC and pollution-haven hypotheses are valid in Pakistan. This study supports Sustainable Development Goal (SDG) 7, advocating affordable clean energy policies to combat energy poverty and promote sustainability in Pakistan, as well as SDG 13, emphasising climate action to ensure both environmental protection and continued economic investment. Considering the SDG targets (2030), policy recommendations are proposed for Pakistan to achieve sustainable development.

KEYWORDS: energy poverty, poverty, SDG goals, institutional quality, globalisation, environmental degradation

Introduction

Human economic activities affect environmental degradation worldwide (Maurya et al., 2020). Environmental issues are the result of natural resource depletion and environmental degradation, which harm air, water, soil, animals, and humans and cause natural disasters such as floods, rising temperatures, and forest fires (Kumar et al., 2020). Environmental degradation increases with the limited availability of advanced energy sources, leading to energy poverty (Addai et al., 2022; Dimnwobi et al., 2023).

Ahmad et al. (2019) demonstrated that access to modern energy resources, especially electricity, is crucial for human well-being, and its scarcity adversely affects the well-being and increases environmental degradation. Yahong et al. (2022) indicated that energy poverty causes environmental degradation in developing economies, suggesting that investment in clean fuels and technology can achieve sustainable development. Zhao et al. (2021) conducted an investigation in China using panel data for Chinese provinces and indicated that environmental degradation has a positive relationship with energy poverty. Baloch et al. (2020) stated that energy poverty and poverty are interconnected with each other, both causes increasing the environmental deterioration around the world. They indicated that the alleviation of poverty and reduction of environmental issues are the main objectives of the United Nations SDG goals: developing economies of the world are trying to alleviate poverty and reduce income inequality. Dimnwobi et al. (2023); Dong et al. (2023) studied the environmental impacts of poverty in South African countries. They highlighted that poverty and income inequality contribute to environmental degradation; they indicated that energy poverty is strongly associated to dependence on coal, oil, and biomass.

Gyamfi et al. (2021) indicated that reliance on the usage of coal, oil, and gas in developing economies is a major driver of environmental degradation. M. K. Khan et al. (2020) indicated that dependence on fossil fuel energy sources for economic activities heightens environmental issues. Khan and Sun, (2024) stated that in developing countries, specifically Pakistan, the use of coal, oil, and gas causes increased environmental degradation, with coal being a significant contributor.

Abdouli & Hammami (2017) and Gök (2019) indicate that the inflow of FDI relocation increases environmental degradation due to investments in harmful industries worldwide. Muhammad et al. (2021) point out that FDI inflow toward developed economies often reduces environmental degradation. Ilyas and Zulfiqar (2019) and Phimphanthavong (2013) pointed out a U-shaped relationship, indicating that in the initial phase, economic growth heightens environmental conditions, but further growth eventually leads to improvements and reduces environmental issues. Jahanger et al. (2023) and Le and Ozturk (2020) indicated that FDI inflows to developing countries increase with globalisation, and better institutional quality in the home country helps reduce environmental issues

Empirical research indicates that institutional quality and globalisation significantly impact economic growth, FDI inflows, and environmental issues. In studies of African economies, Amegavi et al. (2022); C. E. Yameogo et al. (2021) indicated that institutional quality heightens environmental degradation, while controlling the uptake and with an increase in economic globalisation helps to diminish the environmental-related issues. Shahbaz et al. (2018) indicated that environmental degradation worsens with the increase in globalisation. They further indicate that strong institutional quality and globalisation, along with energy pricing, are essential for boosting GDP growth, which promotes the realisation of long-term environmental sustainability.

In developing economies, economic growth driven by energy prices leads to regulatory violations and worsens environmental degradation. Al-Mulali and Ozturk (2016); Ebaid et al. (2022) indicated that conflicting effects of energy prices on environmental degradation are observed in different studies, and stated that higher prices of energy help to reduce traditional energy resources, thus decreasing the degradation of the environment, while M. K. Khan et al. (2019) suggested that increasing energy prices can exacerbate environmental degradation. Pakistan, a key South Asian country, faces significant energy challenges and relies entirely on imported oil, causing environmental degradation. The achievement of SDGs is essential for Pakistan under the 2030 agenda.

This study is the first to connect SDG 7 (clean energy) and SDG 13 (climate action) to environmental sustainability in Pakistan, which has been ignored in previous research, according to the SDGs target (2030). Based on the SDG goals, this research explores how energy poverty, income inequality, energy consumption, FDI inflow, economic growth, institutional quality, and energy prices affect

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environmental degradation in Pakistan. The environmental Kuznets curve (EKC) hypothesis and pollution heaven hypothesis are validated, further interaction terms in the variables (poverty and economic growth, poverty and FDI inflow, poverty and institutional quality, energy poverty and FDI, energy poverty and economic growth, energy poverty and institutional quality, economic growth and FDI inflow) are used to examine impact on environmental degradation in Pakistan. Understanding the nature of these variables is essential for formulating policies to reduce environmental degradation and achieve sustainable economic growth in Pakistan to help attain the goals of the SDGs. Pakistan not only plays an essential role in South Asian economies, but it also plays a role in other regions, especially in global politics, and has natural resources that attract the developed economies of the world to investment. Mostly previous studies have used the traditional econometric model, in literature the ARDL model is used most frequently, but advanced econometric model we used in this research, the dynamic ARDL simulation model was suggested by Jordan & Philips, (2018), this model facilitates the prediction of both shocks in the independent variables and their corresponding effects on environmental degradation through simulation graphs that is not available in the ARDL model; Further, the robustness of the results was checked with the simple ARDL model. Assessing the results of this research provides insights for policy experts and assistance in formulating strategic plans for environmental sustainability.

Data Description and Methodology

Data Description

Based on the literature, this study included variables with relevance to environmental degradation. Energy poverty is selected based on its role in increasing the dependency on high-emission traditional fuels (Haroon, 2024; Zhao et al., 2024). Poverty and income inequality are included based on literature due to their impact on access to clean energy and sustainable technologies (Li et al., 2024; Ndoya & Asongu, 2024; Wang & Chen, 2022). Energy consumption, economic growth, and FDI inflows are most frequently used drivers of emissions and resource use that cause environmental issues (Adebayo & Rjoub, 2022; Nuță et al., 2024; Roy, 2024). Institutional quality and globalisation influence environmental issues through governance effectiveness and investment flows in green energy projects (Azam et al., 2021; Hussain & Dogan, 2021; Yameogo et al., 2021). Energy prices are included given their role in shaping consumption patterns and their impact on carbon emissions (Ike et al., 2020; Shan et al., 2021, Dao et al., 2024). For missing data of energy poverty, institutional quality regular imputation with the linear interpolation method is applied to fill the missing values. Table 1 shows the data sources and variables for the period 1984–2022 for Pakistan.

Principal Component Analysis (PCA)

Maćkiewicz & Ratajczak (1993) demonstrated that principal component analysis (PCA) is a multivariate technique mostly used to transform correlated variables into a smaller set of uncorrelated components to reduce the dimensions. The PCA process starts with standardising the variables to ensure comparability, followed by the computation of the correlation matrix. Eigenvalues and eigenvectors are then extracted to form principal components for further analysis, that is ordered based on the variance explained. A scree plot (eigenvalues >1) is used to specify the number of components to retain as per (Mesa et al., 2018). Further, the component loadings are used to interpret each variable's contributions; the higher absolute values indicate a stronger influence on the components. In this study, PCA analysis is used for Energy Poverty indicators (E1 to E6, detailed description is given in the appendix), Globalisation's indicators (GB1 to GB3) and institutional quality indicators (IQ1 to IQ6) are included in the appendix.

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Table 1. Variables Description

Variables	Description	Data Source
Carbon Dioxide emission	TERRITORIAL (Gas, Oil, Goal, Gas Flaring, Cement) tCO_2/person	Global Carbon Atlas https://globalcarbonatlas.org/
Energy Poverty	PCA of E1 to E6 (Details in appendix)	World Development Indicator (WDI) World Bank
Poverty	Taken from Households and NPISHs Final consumption expenditure per capita (constant 2015 US$) data	
Income Inequality	Gini coefficient	World Inequality Database https://wid.world/data/
Energy Consumption	Renewable Energy Consumption Per capita	World Development Indicator (WDI) World Bank
Foreign Direct Investment (FDI)	Foreign direct investment, net inflows (% of GDP)	
Economic Growth	GDP Growth (annual %)	
Globalisation	PCA of GB1 to GB3 (Details in appendix)	KOF Swiss Economic Institute website https://kof.ethz.ch/
Energy Prices	Average annual Brent crude oil price (in U.S. dollars per barrel)	Statista website https://www.statista.com/
Institutional Quality	PCA of IQ1 to IQ6 (Details in appendix)	Worldwide Governance Indicators, Database

Based on Table 1, the basic regression equation was used to examine the relationships among the study variables.

$$COEmission_t = \beta_0 + \beta_1 EPrty_t + \beta_2 Prty_t + \beta_3 Inility_t + \beta_4 ECion_t + \beta_5 FDI_t + \beta_6 GDP_t + \beta_7 Iqity_t + \beta_8 Glb_t + \beta_9 Epces_t + \varepsilon_t. (1)$$

This study examined the validity of the pollution haven hypothesis and the EKC using squared FDI and GDP in (equation 2).

$$COEmission_t = \beta_0 + \beta_1 EPrty_t + \beta_2 Prty_t + \beta_3 Inility_t + \beta_4 ECion_t + \beta_5 FDI_t + \beta_6 SqrFDI_t + \beta_7 GDP_t + \beta_8 SqrGDP_t + \beta_9 Iqity_t + \beta_{10} Glb_t + \beta_{11} Epces_t + \varepsilon_t. (2)$$

To enhance the scope of this study, we used the interaction terms in Equation 2 for the following variables (poverty and economic growth, poverty and FDI inflow, poverty and institutional quality, energy poverty and FDI, energy poverty and economic growth, energy poverty and institutional quality, economic growth, and FDI inflow).

$$COEmission_t = \beta_0 + \beta_1 Prty_t + \beta_2 EPrty_t + \beta_3 GDP_t + \beta_4 FDI_t + \beta_5 Prty * GDP_t + \beta_6 Prty * FDI_t + \beta_7 Prty * Iqity_t + \beta_8 EPrty * FDI_t + \beta_9 EPrty * GDP_t + \beta_{10} EPrty * Iqeity_t + \beta_{11} GDP * FDI_t + \varepsilon_t. (3)$$

In equation (3) environmental degradation is measured by the COEmission, the interaction term of poverty and economic growth that is indicated by Prty*GDP, poverty and foreign direct investment interaction term is indicated by Prty*FDI, Prty and Iqity is used for interaction term of poverty and institutional quality, further in this study interaction term of different variables with energy poverty is checked, EPrty*FDI show the energy poverty interaction with foreign direct investment, Eprty*GDP show the interaction term of energy poverty and economic growth, energy poverty and institutional quality is indicated by EPrty*Inqeity, GDP*FDI indicates the interaction term of economic growth and FDI, is error term in the above equation.

PCA Analysis for Energy Poverty

Table 2. Results of PCA Eigenvalue

PC	Eigenvalue	% variance
1	2732.53	91.96
2	171.28	5.76
3	66.78	2.25
4	0.48	0.02
5	0.19	0.01
6	0.04	0.00

Table 2 indicates the extraction of six elements of the PCA, in which the first two components accounted for 97.72% of the total variance. Component 1 has an eigenvalue of 2732.53, which explains 91.96% of the total variance, while Component 2 additionally explains 5.76% (eigenvalue = 171.28). The (PC3–PC6) components were negligible (<2.3% combined), which confirms that the two-dimensional representation sufficiently captures the underlying data structure for energy poverty.

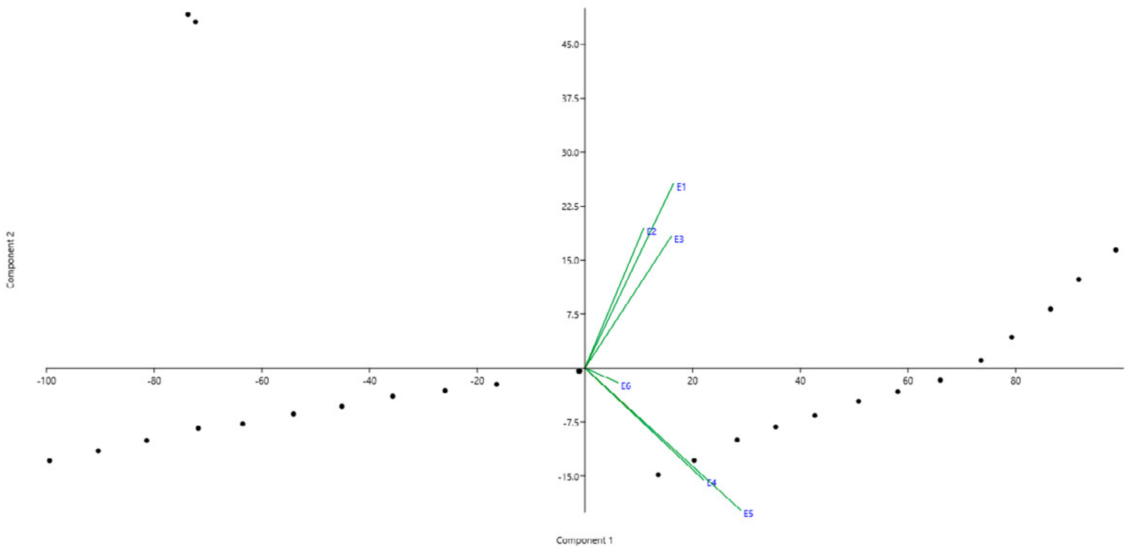

Figure 1. PCA Biplot for Energy Poverty

The PCA biplot (Figure 1) indicates that Component 1 represents variation in energy access indicates (E4–E6), while the Component 2 shows access to clean cooking fuels (E1–E3). The above graph indicates high intra-group coherence observed, with limit correlation between electricity and cooking variables that are used for energy poverty. Based on the biplot graph, electricity elements account for the majority of explained variance, which highlights distinct dimensions of energy access.

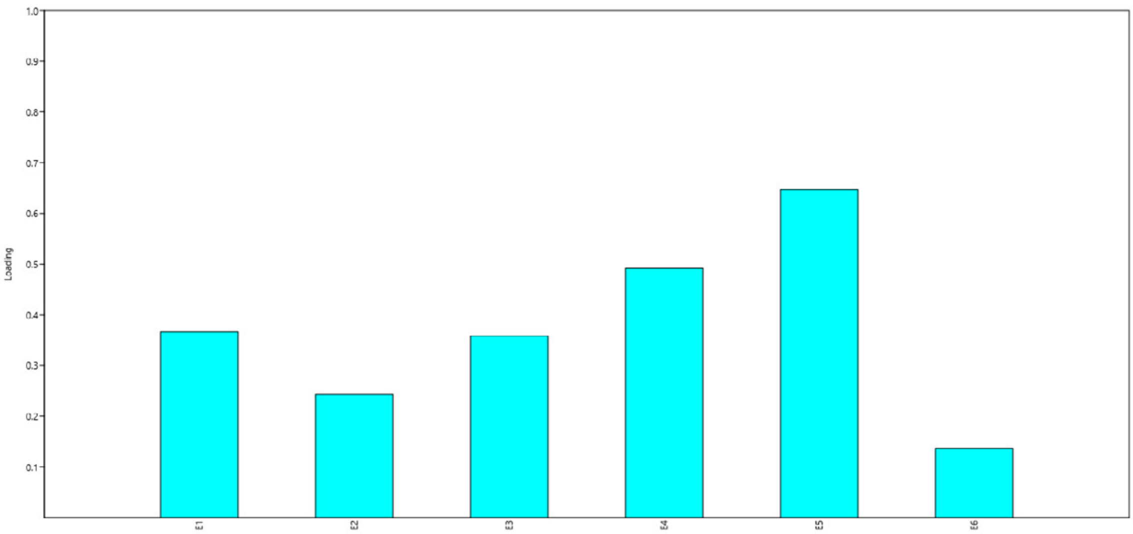

Figure 2. Variable Loadings for Principal Component 1

Figure 2 indicates that PC1 is primarily influenced by E5 and E4, highlighting rural and total electricity access as dominant contributors. E1–E3 show moderate influence, while E6 contributes minimally. This indicates that PC1 mainly captures variation in rural electricity access, with secondary input from clean cooking indicators.

Table 3. PCA Loading Matrix

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
E1	0.37	0.57	0.22	0.03	-0.69	0.10
E2	0.24	0.43	0.56	-0.10	0.64	-0.16
E3	0.36	0.41	-0.79	0.00	0.27	-0.03
E4	0.49	-0.35	0.03	0.40	-0.09	-0.69
E5	0.65	-0.44	0.06	-0.45	0.03	0.42
E6	0.14	-0.05	0.08	0.79	0.18	0.56

Table 3 indicates that PC1 (91.96% variance) is primarily driven by electricity access, especially rural (E5 = 0.65) and total (E4 = 0.49). PC2 (5.76%) captures clean cooking access, with high loadings from E1 (0.57), E2 (0.43), and E3 (0.41), and inverse contributions from E4 and E5. Remaining components contribute minimally and lack coherent structure, justifying focus on the first two PCs.

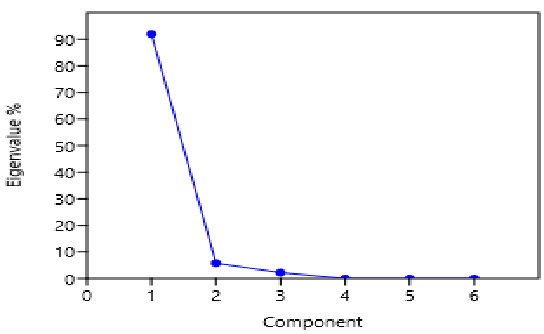

Figure 3. Scree Plot

The scree plot (Figure 3) shows a steep decline after the first component, with PC1 explaining over 90% of the variance. PC2 contributes marginally, while PC3–PC6 account for negligible variation. The sharp elbow at PC2 confirms that the first two components capture nearly all meaningful

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structure, validating dimensionality reduction to a two-component solution. PCA for Globalisation and Institutional quality is included in the appendix at the end of the paper.

PCA Analysis for Institutional quality

Table 4. PCA Eigenvalue

PC	Eigenvalue	% variance
1	100.622	49.272
2	46.3177	22.681
3	30.6642	15.015
4	17.8261	8.729
5	5.92471	2.9012
6	2.86236	1.4016

The first two principal components explain 71.95% of the total variance, with PC1 accounting for 49.27% and PC2 for 22.68% as indicated in Table 4. PC3 contributes an additional 15.02%, cumulatively capturing 86.97% of the variance across the first three components. The remaining components (PC4–PC6) add marginal explanatory power, justifying a dimensionality reduction to three components for results analysis.

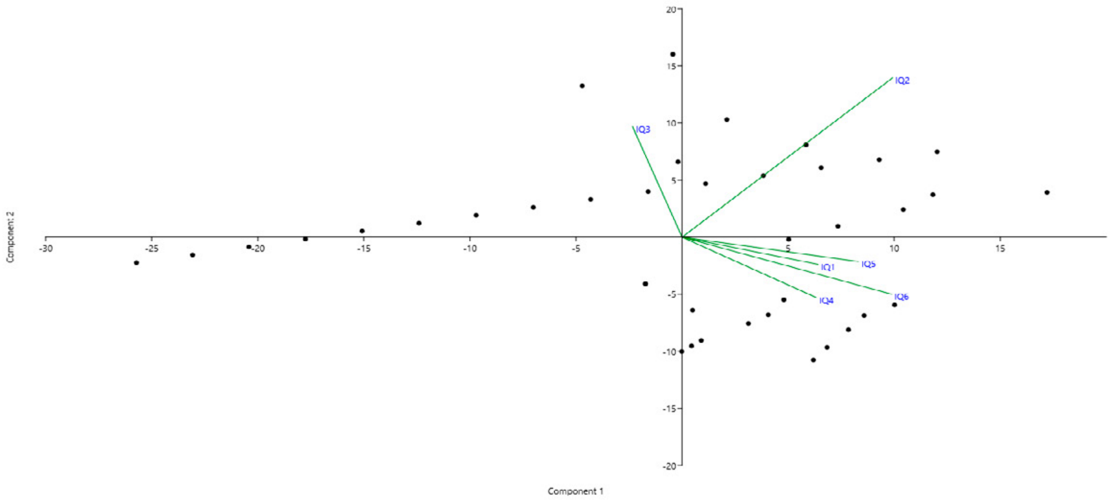

Figure 4. PCA Biplot for Institutional Quality

The biplot (Figure 4) reveals that PC1 captures the dominant variation in institutional quality, with strong positive loadings from IQ1 (Control of Corruption), IQ4 (Regulatory Quality), IQ5 (Rule of Law), and IQ6 (Voice and Accountability). PC2 is primarily shaped by IQ2 (Government Effectiveness) and IQ3 (Political Stability), which project more distinctly along the vertical axis. The angular separation between vectors suggests moderate correlation among most indicators, while the spatial dispersion of observations indicates heterogeneity in institutional quality across units.

PC1 is primarily shaped by IQ2 (Government Effectiveness), IQ6 (Voice and Accountability), and IQ5 (Rule of Law), each showing high positive loadings indicated in (Figure 5). Moderate contributions arise from IQ1 and IQ4, while IQ3 (Political Stability) contributes negatively, suggesting it diverges from the shared variance structure of the other indicators. This pattern indicates PC1 reflects institutional strength, with political stability acting as a contrasting dimension.

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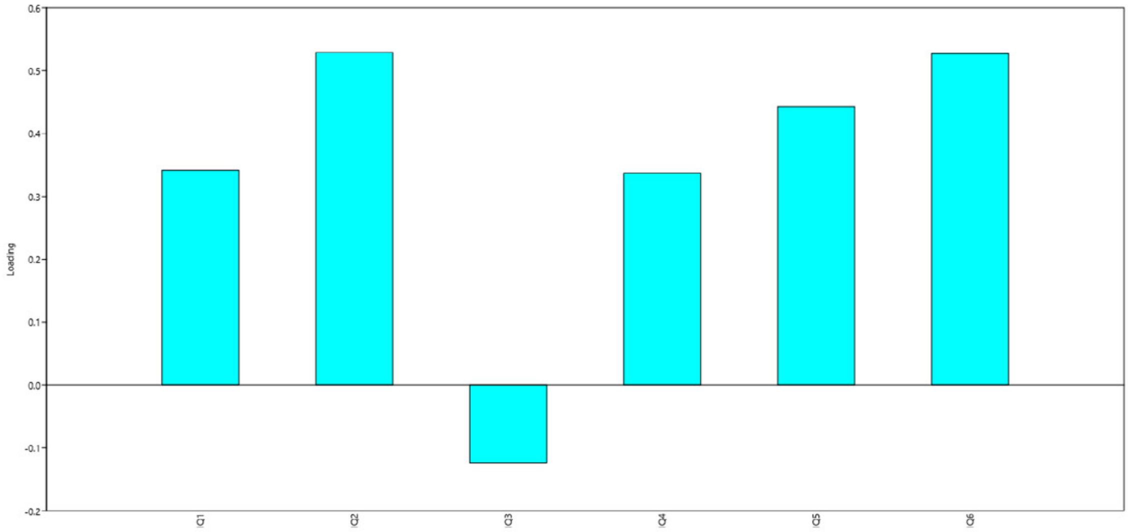

Figure 5. Variable Loadings for Principal Component 1

Table 5. PCA Loading Matrix

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
IQ1	0.34	-0.13	-0.63	0.53	0.31	-0.31
IQ2	0.53	0.74	-0.17	-0.28	-0.23	-0.09
IQ3	-0.12	0.52	0.41	0.34	0.66	0.05
IQ4	0.34	-0.28	-0.03	-0.64	0.63	0.07
IQ5	0.44	-0.11	0.07	0.29	-0.08	0.83
IQ6	0.53	-0.27	0.63	0.18	-0.15	-0.45

PC1 is mainly defined by high positive loadings from IQ2 (0.53) and IQ6 (0.53), alongside moderate contributions from IQ5 (0.44), IQ1 (0.34), and IQ4 (0.34), reflecting a general dimension of institutional governance in (Table 5). PC2 is shaped by IQ2 (0.74) and IQ3 (0.52), indicating a distinct axis of government effectiveness and political stability. PC3 captures divergent patterns, with strong opposing contributions from IQ1 (−0.63) and IQ6 (0.63), suggesting structural contrasts in corruption control and voice and accountability. Remaining components explain finer variance structures, but their interpretability is less robust.

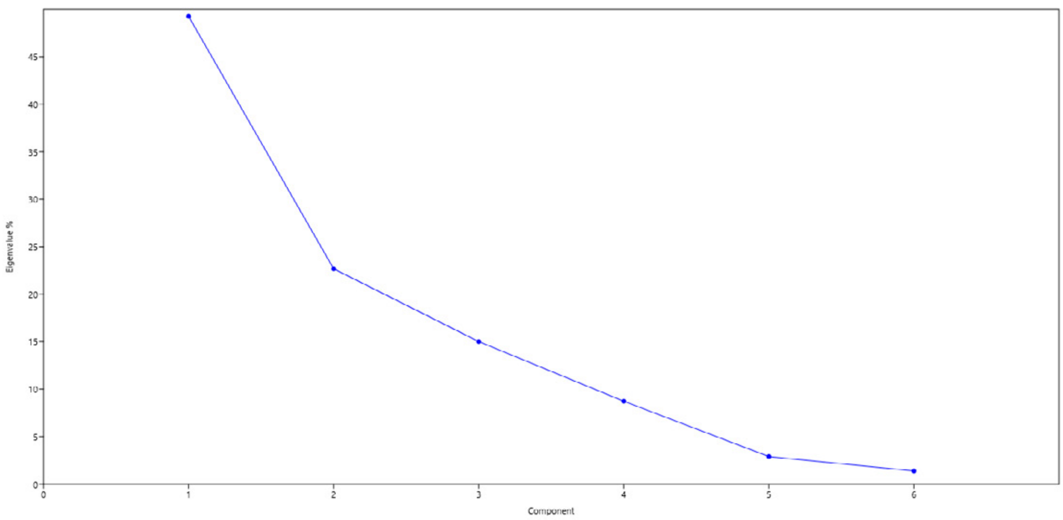

Figure 6. Scree Plot

The scree plot (Figure 6) shows a steep decline after the first component, with PC1 explaining the largest proportion of variance. A visible elbow at PC3 suggests that the first three components collectively capture the most meaningful structure. Subsequent components contribute marginally, supporting dimensionality reduction to three components.

PCA component analysis for Globalisation

Table 6. PCA Eigenvalue

PC	Eigenvalue	% variance
1	71.26	66.17
2	28.86	26.80
3	7.57	7.03

The PCA results (Table 6) for globalisation indicate that the first three principal components (PC1–PC3) explain 100% of the variance. PC1, which accounts for 66.17% of the variance, is the dominant component, capturing the primary patterns of globalisation. PC2 explains an additional 26.80%, reflecting a secondary factor, while PC3 contributes 7.03%, representing a finer aspect of globalisation. These findings suggest that the first three components comprehensively describe the underlying structure of globalisation in the dataset.

The biplot (Figure 7) shows that PC1 and PC2 capture most of the variance in the globalisation indicators. GB3 (Political Globalisation) shows a strong positive loading along PC1, indicating it is the most influential factor in this dimension. GB2 (Social Globalisation) and GB1 (Financial Globalisation) are more evenly distributed along both axes, suggesting that they contribute to multiple dimensions of globalisation. The spread of points in the plot indicates significant variation across the sample, with most observations being more aligned with PC1.

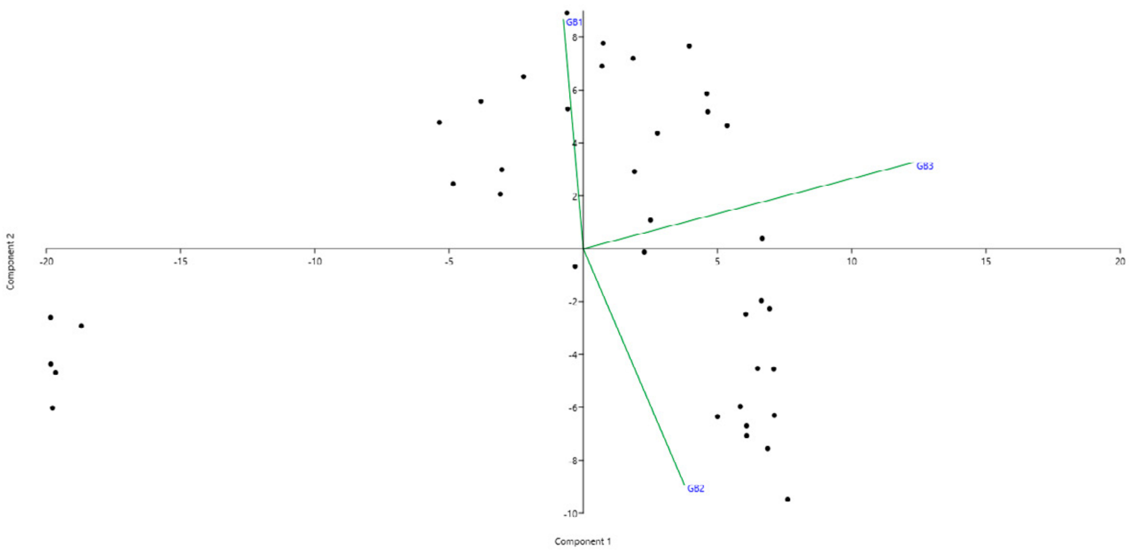

Figure 7. PCA Biplot for Globalisation

The loading plot (Figure 8) indicates that GB3 (Political Globalisation) has the highest contribution to the first principal component (PC1), with a loading close to 0.90, reflecting its dominant influence on the global integration dimension captured by PC1. GB2 (Social Globalisation) follows with a moderate contribution, while GB1 (Financial Globalisation) has the smallest loading, indicating it plays a less prominent role in this principal component.

Figure 8. Variable Loadings for Principal Component 1

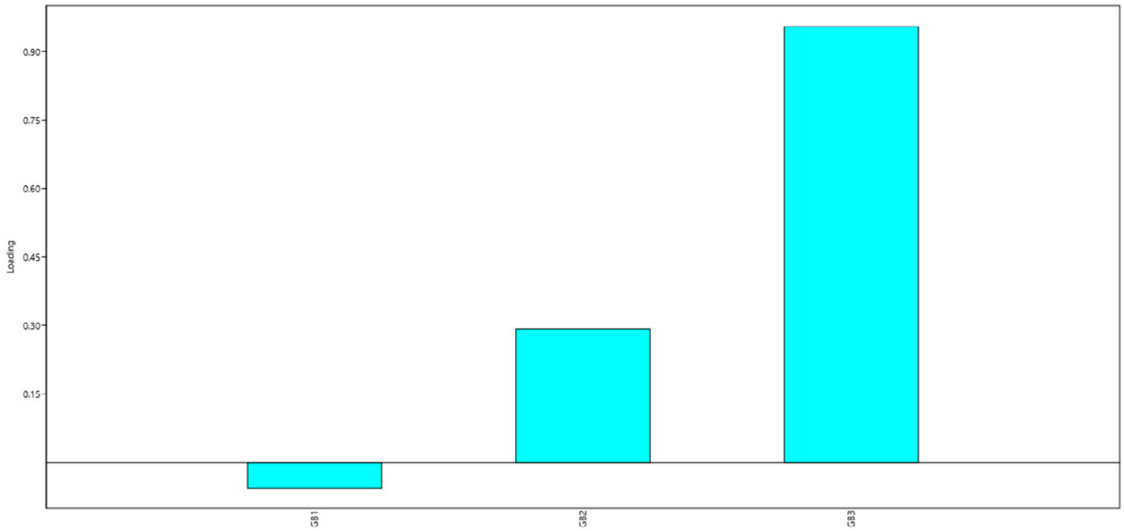

Table 7. PCA Loading Matrix

	PC 1	PC 2	PC 3
GB1	-0.06	0.67	0.74
GB2	0.29	-0.69	0.66
GB3	0.95	0.25	-0.16

The PCA loading matrix (Table 7) indicates that PC1 is primarily driven by GB3 (Political Globalisation) with a strong positive loading (0.95), highlighting its dominant role in this component. GB2 (Social Globalisation) has a moderate positive loading (0.29), while GB1 (Financial Globalisation) shows a negligible negative loading (-0.06). PC2 is most influenced by GB2, which has a strong negative loading (-0.69), while GB1 and GB3 have weaker positive contributions. In PC3, GB1 and GB2 have moderate positive loadings (0.74 and 0.66), indicating a stronger role for financial and social globalisation, while GB3 contributes minimally (-0.16).

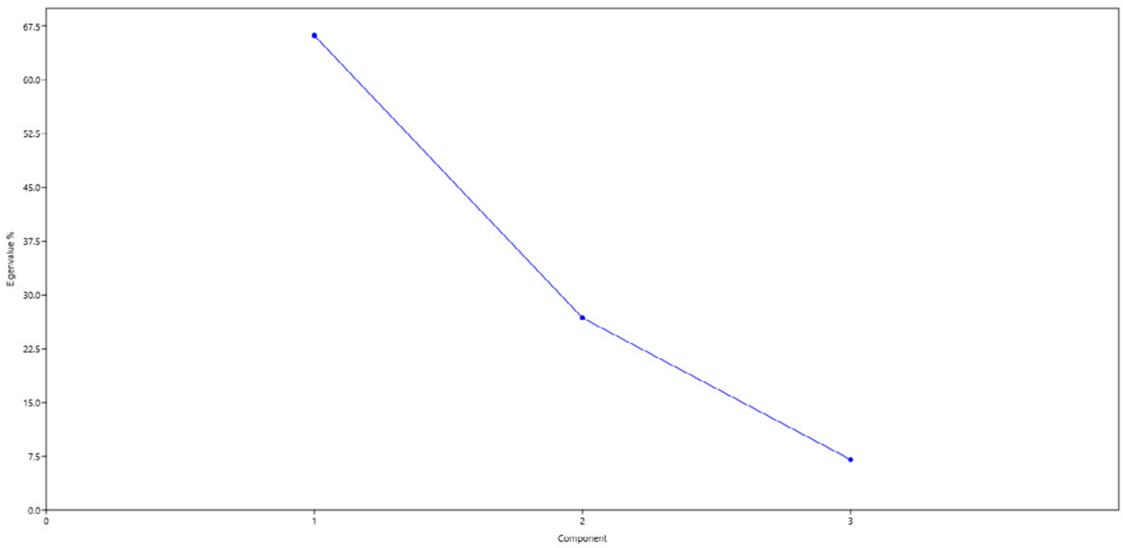

Figure 9. Scree Plot

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The scree plot (Figure 9) shows a clear elbow at PC1, where the variance explained by each component sharply decreases. PC1 accounts for the highest proportion of the total variance (around 67.5%), followed by PC2 and PC3, which capture significantly less variance. This pattern suggests that the first principal component is the most influential in explaining the dataset's structure, while the additional components provide diminishing returns. Based on this, it is recommended to retain the first component for further analysis, as it represents the majority of the data's variance.

Econometric Methodology

In time series data, the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test are applied for stationarity. The findings show mixed stationarity at I(0) and I(1), supporting the use of the Dynamic ARDL model.

Cointegration Test

This study used the bounds-testing approach to assess cointegration in the study variables. If the calculated F-statistic exceeds the upper bound, cointegration is confirmed; if it falls below, no cointegration exists; and if it lies between the bounds, the result is inconclusive. Based on the results, cointegration exists in the study variables.

$$\begin{aligned}\Delta COEmission_t = {} & \beta_0 + \beta_1 EPrty_{t-i} + \beta_2 Prty_{t-i} + \beta_3 Inility_{t-i} + \beta_4 ECion_{t-i} + \beta_5 FDI_{t-i} \\ & + \beta_6 SqrFDI_{t-i} + \beta_7 GDP_{t-i} + \beta_8 SqrGDP_{t-i} + \beta_9 Iqity_{t-i} + \beta_{10} Glb_{t-i} \\ & + \beta_{11} COEmission_{t-i} + \beta_{12} Epces_{t-i} + \sum_{i=1}^{n} \partial_1 \Delta EPrty_{t-i} + \sum_{i=1}^{n} \partial_2 \Delta Prty_{t-i} \\ & + \sum_{i=1}^{n} \partial_3 \Delta Inility_{t-i} + \sum_{i=1}^{n} \partial_4 \Delta ECion_{t-i} + \sum_{i=1}^{n} \partial_5 \Delta FDI_{t-i} + \sum_{i=1}^{n} \partial_6 \Delta SqrFDI_{t-i} \\ & + \sum_{i=1}^{n} \partial_7 \Delta GDP_{t-i} + \sum_{i=1}^{n} \partial_8 \Delta SqrGDP_{t-i} + \sum_{i=1}^{n} \partial_9 \Delta Iqity_{t-i} + \sum_{i=1}^{n} \partial_{10} \Delta Glb_{t-i} \\ & + \sum_{i=1}^{n} \partial_{11} \Delta Epces_{t-i} + \sum_{i=1}^{n} \partial_{12} \Delta COEmission_{t-i} + \varepsilon_t. (4)\end{aligned}$$

In the above Bounds test Equation 4, Δ represents the change, whereas t-i denotes lag selection based on the BIC criteria. Based on the confirmation of the cointegration, the Dynamic Autoregressive Distributed Lag (ARDL) simulation model estimates both the long-run and short-run relationships in the study variables by providing robust results even when the variables are integrated at different levels, that is, I(0) and I(1), as compared to other time series models.

Auto Regressive Distributed Lags (ARDL) model

Pesaran et al. (2001) introduced the ARDL approach, and Haug (2002) demonstrated that the results of the ARDL approach are robust and consistent with small datasets as compared to other types of time series models. The ARDL approach accommodates integrated variables I(0) and I(1) and can identify multiple long-run relationships, which is not possible in traditional time series methods. This method offers flexibility in lag selection and variable inclusion, but in other time-series models, the same order of integration is required. The long-run ARDL is estimated using equation (5).

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$$\Delta COEmission_t = \beta_0 + \sum_{i=1}^{n} \partial_1 EPrty_{t-i} + \sum_{i=1}^{n} \partial_2 Prty_{t-i} + \sum_{i=1}^{n} \partial_3 Inility_{t-i} + \sum_{i=1}^{n} \partial_4 ECion_{t-i} + \sum_{i=1}^{n} \partial_5 FDI_{t-i} + \sum_{i=1}^{n} \partial_6 SqrFDI_{t-i} + \sum_{i=1}^{n} \partial_7 GDP_{t-i} + \sum_{i=1}^{n} \partial_8 \Delta SqrGDP_{t-i} + \sum_{i=1}^{n} \partial_9 Iqity_{t-i} + \sum_{i=1}^{n} \partial_{10} Glb_{t-i} + \sum_{i=1}^{n} \partial_{11} Epces_{t-i} + \sum_{i=1}^{n} \partial_{12} COEmission_{t-i} + \varepsilon_t \,. (5)$$

Model 5 demonstrates that the elasticities in the long term, denoted by ∂, were selected by applying the optimal lag length selected by the BIC criteria. The error correction model is shown in Model 6.

$$\Delta COEmission_t = \beta_0 + \sum_{i=1}^{n} \infty_1 \Delta EPrty_{t-i} + \sum_{i=1}^{n} \infty_2 \Delta Prty_{t-i} + \sum_{i=1}^{n} \infty_3 \Delta Inility_{t-i} + \sum_{i=1}^{n} \infty_4 \Delta ECion_{t-i} + \sum_{i=1}^{n} \infty_5 \Delta FDI_{t-i} + \sum_{i=1}^{n} \infty_6 \Delta SqrFDI_{t-i} + \sum_{i=1}^{n} \infty_7 \Delta GDP_{t-i} + \sum_{i=1}^{n} \infty_8 \Delta SqrGDP_{t-i} + \sum_{i=1}^{n} \infty_9 \Delta Iqity_{t-i} + \sum_{i=1}^{n} \infty_{10} \Delta Glb_{t-i} + \sum_{i=1}^{n} \infty_{11} \Delta Epces_{t-i} + \sum_{i=1}^{n} \infty_{12} \Delta COEmission_{t-i} + \mu ECT_{t-1} + \varepsilon_t. (6)$$

In the above (equation (6), ∞ indicates the elasticities in the short-term, while term demonstrates the error correction term, the speed of adjustment rate towards equilibrium after a shock in the past is measured by the ECT term. Further, the sign μ measures the speed of adjustment, which ranges from 0 to -1, where 0 indicates no convergence, and a negative significant value demonstrates full adjustment in the next period toward equilibrium.

DYNARDL (Dynamic ARDL simulations Model)

Jordan and Philips (2018) demonstrated that the DYNARDL model examines the impact of changes in independent variables on the dependent variable, accounting for both short- and long-term effects through graphical simulations. This is the most advanced time-series model that integrates multiple lags of both the dependent and independent variables with potential long-term relationships (cointegration). The main benefit of using the Dynardl simulation model, such as the simple ARDL model and VAR, is its flexibility in handling variables with different integration orders. Furthermore, dynamic simulations provide clear, visual insights into the effects of the independent variables on the dependent variable over time, making them particularly valuable for interpreting complex relationships and for practical applications in policy analysis and forecasting that were ignored in traditional time series models. The following equation indicates the DYNARDL simulation model.

$$y_t = \alpha_0 + \sum_{i=1}^{p} \emptyset_i y_{t-i} + \sum_{j=0}^{q} \beta_j x_{t-j} + y\left(y_{t-1} - \sum_{k=0}^{m} \theta_k x_{t-k}\right) + \epsilon_t \,. (7)$$

Where in the above equation (7), the first sum indicates the short run dynamics, further indicates $y\left(y_{t-1}-\sum_{k=0}^{m}\theta_k x_{t-k}\right)$ the long run equilibrium relation, i.e. y_t *and* x_t and ϵ_t is the error term.

Results and Discussion

Table 8. Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Carbon Dioxide Emissions	39	124.17	53.46	42.56	223.45
E1	39	37.07	1.09	23.50	52.60
E2	39	14.05	1.00	4.40	31.30
E3	39	80.12	0.86	65.20	86.70
E4	39	84.27	1.07	70.27	95.00
E5	39	77.87	1.45	58.96	93.00
E6	39	96.57	0.28	93.14	100.00
Poverty	39	4.61	3.35	-2.83	13.01
Energy Prices	39	45.15	28.36	14.39	99.06
Energy Consumption	39	13.12	2.57	8.38	18.34
Economic Growth	39	4.45	2.03	-1.27	7.83
Square of Economic Growth	39	23.82	17.50	1.03	61.33
FDI	39	0.85	0.65	0.18	3.04
Square of FDI	39	1.13	2.04	0.03	9.22
GB1	39	30.66	4.33	23.98	38.07
GB2	39	22.10	4.80	15.99	31.53
GB3	39	78.29	8.19	57.87	84.09
IQ1	39	15.65	4.03	7.53	23.78
IQ2	39	31.77	4.43	22.79	39.18
IQ3	39	5.71	3.60	0.51	14.36
IQ4	39	25.30	3.24	15.67	32.09
IQ5	39	22.84	2.61	17.57	31.66
IQ6	39	24.50	3.07	17.10	33.23
Income Inequality	39	0.54	0.01	0.52	0.57

Table 8 indicates the descriptive statistics for all variables, highlighting that the average value of carbon dioxide emissions (CO_2) is 124, with minimum (Min) and maximum (Max) values ranging between 42.557 and 223.45. On average, access to clean fuels and electricity is higher in urban areas, with E6 (access to electricity, urban) showing the highest mean (96.57%) and the lowest variability. Rural areas, however, exhibit much lower access, particularly in clean cooking technologies (E2, 14.05%). Furthermore, the mean value of the energy prices is 45.15 and a SD of 28.361, with Min and Max values of 14.39 to 99.06, indicating that higher energy prices help to reduce environmental degradation in Pakistan. Energy consumption and economic growth have mean values of 13.123 and 4.45, respectively. Globalisation, GB3 (political globalisation) has the highest mean (78.29%), with a considerable range, while GB2 (social globalisation) shows moderate mean access (22.10%). GB1

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(financial globalisation) shows a mean of 30.66% and some variability, indicating differing levels of global economic integration. Institutional quality indicators show moderate variation, with IQ3 (political stability) having the lowest mean (5.71) and highest variability, while IQ2 (government effectiveness) and IQ4 (regulatory quality) suggest more consistent institutional frameworks. The SD value of foreign direct investment (FDI) inflows was 3.036. Institutional quality and income inequality have values of 3.15 and 0.011 SD, respectively.

Table 9. Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Carbon Dioxide Emissions	1.000											
energy poverty	0.729	1.000										
Poverty	0.653	0.078	1.000									
Energy Prices	-0.706	0.617	-0.007	1.000								
Energy Consumption	0.965	0.840	0.070	0.711	1.000							
Economic Growth	0.229	-0.181	0.665	-0.157	-0.214	1.000						
Square of Economic Growth	-0.201	-0.129	0.660	-0.197	-0.198	0.943	1.000					
FDI	0.182	-0.086	-0.028	0.276	0.319	-0.087	-0.089	1.000				
Square of FDI	-0.155	-0.080	-0.071	0.316	0.277	-0.048	-0.067	0.968	1.000			
Globalisation	-0.721	0.501	0.020	0.673	0.782	-0.280	-0.294	0.438	0.347	1.000		
Institutional Quality	-0.521	0.316	0.099	0.194	0.586	-0.279	-0.255	0.244	0.115	0.648	1.000	
Income Inequality	0.145	-0.221	0.149	-0.121	-0.070	0.378	0.394	0.162	0.198	-0.231	0.080	1.000

Table 9 reveals that higher energy poverty decreases environmental sustainability. The results of the correlation indicate that poverty, income inequality, energy use, economic growth, and FDI inflows increase environmental degradation in Pakistan, whereas an increase in energy prices reduces it. The squared terms of GDP and FDI confirm the Environmental Kuznets Curve and Pollution Haven Hypothesis in Pakistan. The findings demonstrate that globalisation and institutional quality increase the sustainability of the environment in Pakistan, indicating their role in reducing environmental degradation. Environmental sustainability and income inequality were positively correlated, indicating that income inequality decreases sustainability in Pakistan.

Table 10. Unit Root Tests

Variables	ADF At Level	ADF at 1st Diff	PP at Level	PP at 1st Diff
Carbon Dioxide Emissions	-0.659(0.8570)	-5.803(0.0000)	-0.626(0.8649)	-5.748(0.0000)
Energy poverty	-2.638(0.0854)	-5.742(0.0000)	-2.999(0.0350)	-5.777(0.0000)
Poverty	-7.248(0.0000)	-11.471(0.0000)	-7.422(0.0000)	-15.679(0.0000)
Energy Prices	-1.133(0.7018)	-5.809(0.0000)	-1.013(0.7485)	-5.786(0.0000)
Energy Consumption	-0.342(0.9194)	-4.941(0.0000)	-0.411(0.9082)	-4.936(0.0000)
Economic Growth	-4.518(0.0002)	-8.590(0.0000)	-4.496(0.0002)	-10.016(0.0000)
Square of Economic Growth	-4.317(0.0004)	-8.694(0.0000)	-4.298(0.0004)	-9.456(0.0000)
FDI	-2.043(0.2680)	-4.141(0.0000)	-2.438(0.1314)	-4.107(0.0004)
Square of FDI	-2.135(0.2306)	-3.830(0.0026)	-2.456(0.1265)	-3.671(0.0045)
Globalisation	-2.419(0.1364)	-5.548(0.0000)	-2.403(0.1048)	-5.595(0.0000)
Institutional Quality	-2.908(0.0444)	-5.537(0.0000)	-2.920(0.0430)	-5.527(0.0000)
Income Inequality	-2.100(0.2445)	-4.274(0.0005)	-2.363(0.1524)	-4.144(0.0008)

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The findings in Table 10 revealed that the ADF test indicates that at level 1(0), the variables carbon dioxide emissions, energy proxy, energy prices, energy consumption, FDI, globalisation, and income inequality are stationary, while stationary at I(I). The findings demonstrate that the ADF and PP tests confirm mixed stationarity, thus validating the use of the Dynamic ARDL simulation model.

Table 11. VAR Lag Order Selection Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-959.0248	NA	4.12e+08	51.05393	51.52797	51.22259
1	-640.8510	435.3957*	16408.28*	40.67637*	46.36482*	42.70028*
* Indicates lag order selected by the criterion						

Findings in Table 11 are used to select the most suitable lag. The findings indicate that lag 1 is selected as supported by most of the tests in the table above.

Table 12. Cointegration Test

Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	9.32	10%	1.76	2.77
K	11	5%	1.98	3.04
		2.5%	2.18	3.28
		1%	2.41	3.61

The findings of the Bounds in Table 12 confirm cointegration, as the examined F-statistic exceeds the upper bound of the bounds test.

Table 13. Dynamic ARDL Simulation Long Run and Short Run Results

	Dependent_Variable_CO_2_Emission	
	Long_Run_Results	Short_Run_Results
Error_correction_Term		-0.805***
		(-5.30)
Energy_Poverty	139.5	115.3***
	(1.72)	(4.48)
Energy_Prices	-1.447**	-2.621***
	(-3.73)	(-5.31)
Globalisation	20.98*	39.01***
	(2.82)	(4.91)
Poverty	2.550**	3.474**
	(3.24)	(3.21)
Energy_Consumption	-20.81	-64.73
	(-0.46)	(-1.78)
Economic_Growth	261.8**	419.3**
	(3.19)	(-3.86)
Sqr_of_Economic_Growth	-0.546*	1.070***
	(-2.67)	(5.43)
FDI	87.42	-157.0*

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	Dependent_Variable_CO_2_Emission	
	Long_Run_Results	Short_Run_Results
	(1.58)	(-2.61)
Sqr_of_FDI	-4.844*	-8.516***
	(-2.77)	(-4.64)
Institutional_Quality	-2.467**	-4.393**
	(-3.02)	(-3.91)
Income_Inequality	848.0**	-1525.3***
	(3.23)	(-4.95)
_cons		2137.6***
		(4.44)
N	38	
R_Square	0.9131	
F(23, 14)	6.40(0.0004)	
Simulations	5000	
White's test	39.00(0.4246)	
ARCH	0.080(0.7771)	
Breusch-Godfrey serial correlation LM test	0.247(0.6191)	
Skewness	2.97(0.9911)	
Kurtosis	2.59(0.1073)	

In the above table t statistics is indicated in the parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 13 shows the estimated Dynamic ARDL simulation (short- and long-run), indicating that energy poverty in Pakistan has a positive and non-statistically significant contribution to environmental degradation, implying that environmental degradation in Pakistan increases with an increase in energy poverty, whereas the short-run model shows that environmental degradation in Pakistan is positively influenced by energy poverty. Pakistan aims to be in the list of upper middle-class economies by adopting the SDG goals. As Pakistan strives to achieve the 7th SDG goal 7 by recommending policies that are helpful in addressing the issue of energy accessibility, but also ensure that access to energy resources is environmentally friendly. The results are the same as those highlighted by (Ehsanullah et al., 2021; Zhao et al., 2021). Ehsanullah et al., (2021) examined the energy insecurity and its effect on energy poverty in G7 countries. They demonstrated that energy poverty increased with energy insecurity. Zhao et al., (2021) indicated that energy poverty is a global issue that exacerbates environmental degradation around the world.

The examined finding reveals that rising energy prices significantly reduce environmental degradation, contributing to sustainability in Pakistan, but increasing the energy prices motivates householders to use the traditional energy sources for cooking and other uses that boost the environmental degradation in a real situation in Pakistan. An increase in energy prices helps reduce energy consumption and motivates end users to use sustainable and eco-friendly sources of energy to achieve sustainable development. The energy price findings are similar to (Abbasi et al., 2021; Dabachi et al., 2020). Abbasi et al. (2021) examined the association between energy prices, economic complexity, and environmental sustainability in 18 leading countries; they indicate that energy prices help to increase the sustainability. Dabachi et al., (2020) pointed out the bidirectional relationship of energy prices with the environment in OPEC economies.

FDI inflows are positively and significantly associated with environmental degradation in Pakistan. A positive impact is caused by industrial investment by developed economies in Pakistan, which has increased environmental issues. Pakistan must allow investment in sustainable and environmentally friendly projects to help increase environmental sustainability for sustainable development. The Sustainable Development Goal (SDG 9) aims to foster innovation and build resilient infrastructure to achieve sustainable industrialisation and reduce environmental impact by using sustainable and environmentally friendly industries through globalisation for investment in Pakistan. Wen et al. (2021) used panel data for Asian countries and found that financial globalisation and non-renewable energy use negatively affect the environment.

The findings show that rising poverty decreases environmental sustainability in Pakistan, stressing the need for integrated policies that address poverty reduction alongside environmental protection. Amar and Pratama (2020) assessed the association of poverty and economic growth with the environment and found that income inequality and poverty decrease with an increase in economic growth. The relationship between economic growth, poverty reduction, and inequality helps to increase the sustainability of the environment in ASEAN countries. Energy consumption has an insignificant negative effect on environmental degradation, whereas increased renewable energy use enhances environmental sustainability in Pakistan. Our results contradict those reported by Ulussever et al. (2023). Ulussever et al. (2023) studied the relation of energy consumption and geopolitical risk with a sustainable environment. They indicate that in GCC economies, both increases in energy consumption and higher energy prices are associated with an increase in environmental issues. EKC hypothesis was verified in Pakistan through the squared term of economic growth. These findings align with those of Ike et al. (2020), confirming the EKC hypothesis using panel data analysis across the G7 economies. The findings demonstrated that the square of FDI validated the Pollution Haven Hypothesis (PHH) in Pakistan. Doubling FDI helps increase environmental sustainability in Pakistan, and our findings are similar to those of Munir and Ameer (2020). Munir and Ameer (2020) revealed that a positive shock in FDI inflows is responsible for the increasing environmental degradation in Pakistan.

Institutional quality plays an essential role in economic development and sustainable environments. Effective environmental rules and regulations can help increase environmental sustainability in Pakistan. An increase in institutional quality causes an increase in environmental sustainability in Pakistan. Our results contradict Jahanger et al. (2023). The authors indicate that environmental sustainability decreases with an increase in institutional quality and globalisation. Another major element of environmental degradation is income inequality; the income level distributes the population into different income groups. Income inequality findings indicate a positive impact on the degradation of the environment in the long term, although in the short run, income inequality helps reduce environmental issues. Our findings are the same (Musa et al., 2021), revealing that environmental issues decrease with high institutional quality. The error correction term shows the speed of adjustment toward the long-run equilibrium, which is negative and statistically significant, indicating that approximately 80.5% of the deviations are corrected after a shock in each period. The results demonstrate that 91% of the variation is explained by the variables used, while the remaining 9% is due to other external elements; the model is fit as per the findings of the F-statistics. The findings confirm the absence of heteroskedasticity and serial correlation and indicate that the residuals are normally distributed.

Table 14. Robustness Check with ARDL

Variables (Carbon Emissions Dependent variable)	Long-Run ARDL	Short-Run ARDL
	Coeff	Coeff
Poverty	0.931* (2.612)	0.195*** (5.023)
GDP	0.582* (2.051)	0.501** (3.188)
FDI	0.643*** (3.923)	0.939*** (4.076)
Income Inequality	0.591*** (3.975)	0.434** (2.855)

Variables (Carbon Emissions Dependent variable)	Long-Run ARDL	Short-Run ARDL
	Coeff	Coeff
Energy Poverty	0.139** (3.393)	0.811*** (5.522)
Poverty*GDP	0.523* (1.994)	0.874* (2.184)
Poverty*FDI	0.159* (2.015)	0.493** (3.329)
Poverty*Income_Inequality	0.882* (2.264)	0.184 (1.676)
Energy_poverty*GDP	0.796*** (3.640)	0.934** (2.947)
Energy_poverty*FDI	0.834*** (3.554)	0.462 (1.739)
Energy_poverty*Income Inequality	0.738*** (3.479)	0.652 (1.619)
GDP*FDI	-0.674** (-2.778)	-0.857*** (-3.938)
_cons		0.242*** (3.941)
CointEq (-1)		-1.546** (-2.816)

The ARDL regression results provide a comprehensive account of the socio-economic determinants of carbon emissions in Pakistan. The findings indicate that poverty emerges as a significant element of environmental degradation in both the long and short run. The long-run coefficient (0.931; t = 2.612) underscores the structural link between deep-rooted poverty and high emissions, while the short-run coefficient (0.195; t = 5.023) highlights the immediate ecological consequences of rising poverty levels. GDP is positively associated with carbon emissions in both (long-run: 0.582; t = 2.051; short-run: 0.501; t = 3.188), the results of the GDP support the scale effect hypothesis; the findings indicate that economic growth intensifies environmental degradation.

The findings demonstrate that foreign direct investment (FDI) significantly increases emissions in both the long term (0.643; t = 3.923) and the short term (0.939; t = 4.076), it indicates that capital inflows are directed toward pollution-intensive activities, which is assisted by weak regulation. The short-run results demonstrate that the environmental costs of FDI appear quickly. Further, the findings of the ARDL model indicate that income inequality also exhibits a positive relationship with carbon emissions in the (long-run: 0.591; t = 3.975; short-run: 0.434; t = 2.855), which reflects that wealthier people use more energy and resources, which increases pollution, while environmental societies struggle to work together to protect the environment. Energy poverty exacerbates the carbon emissions both (long-run: 0.139; t = 3.393; short-run: 0.811; t = 5.522), the findings demonstrate that the results of the short-run effect indicate reliance on carbon-intensive fuels due to unequal access to clean energy.

Further in this study, we examined the interaction effects for different variables. The findings of the interaction term between poverty and GDP are positively significant in both the long run (0.523; t = 1.994) and the short run (0.874; t = 2.184), the findings indicate that the environmental impact of economic growth increases with the interaction of poverty. Further, the findings indicate that the interaction of poverty with FDI is significant and positively impacts emissions in both (long-run: 0.159; t = 2.015; short-run: 0.493; t = 3.329), the findings demonstrate that FDI inflows increase carbon emissions. The findings demonstrate that interaction between poverty and income inequality has a significant impact only in the long run (0.882; t = 2.264), indicating a positive effect on emissions, while in the short run, the effect is statistically insignificant (0.184; t = 1.676).

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Furthermore, the findings indicate that energy poverty's interaction with GDP is positive and significant (long-run: 0.796; t = 3.640; short-run: 0.934; t = 2.947), the findings indicate that economic growth without simultaneous improvements in energy access increases environmental degradation. Further, the results are evident in the interaction between energy poverty and FDI, significantly increasing the carbon emission in the long run (0.834; t = 3.554), but in the short run (0.462; t = 1.739), it has no effect. The findings demonstrate the delayed environmental costs of investment in energy-deficient regions. Similar results were pointed out in the interaction term between energy poverty and income inequality; the findings indicate a statistically significant effect only in the long run (0.738; t = 3.479).

The findings of the interaction term between GDP and FDI indicate a negative and statistically significant impact on the carbon emission in Pakistan in both the long run (-0.674; t = -2.778) and the short run (-0.857; t = -3.938). The findings suggest that when economic growth interacts with FDI inflow, emissions are mitigated due to the adoption of cleaner technologies for energy, high-quality governance and stringent environmental rules associated with investment. The findings of the error correction term indicate a negative and statistically significant (-1.546; t = -2.816) coefficient that confirms the existence of a stable long-run equilibrium and indicates a rapid adjustment process toward equilibrium following short-run deviations.

Discussions

The results indicate that poverty remains a critical element of environmental degradation in Pakistan. These findings aligned with the ecological modernisation theory and early empirical research suggesting that poor populations mostly depend on biomass and traditional energy resources, which increase carbon emissions. Mabogunje (2002) emphasised that poverty motivates the usage of traditional energy resources that contribute to increasing the ecological vulnerability, which collectively increases the environmental degradation. The findings indicate that significant short-run and long-run impacts suggest that poverty alleviation should be an essential element of environmental policy to reduce environmental issues, not just for social justice, but also for sustainability.

The GDP findings indicate a positive influence on carbon emissions, which supports the "scale effect" aspect of the Environmental Kuznets Curve (EKC). The finding indicates that economic expansion, in the early stages, increases environmental degradation due to industrial activity, fossil fuel use, and infrastructure development. Our findings are the same as those of Mrabet et al. (2017). They indicated that Qatar's economic growth has a positive relationship with environmental degradation, which challenges the EKC hypothesis in resource-intensive economies. However, they further indicated that interaction terms suggest that GDP's environmental impact is conditioned by other factors, particularly the FDI and access to energy.

The environmental consequences of the foreign direct investment support the concerns in the pollution havens literature. The findings demonstrate that foreign capital inflows toward host countries increase emissions, especially in the short run. This is due to the relocation of carbon-intensive industries to host countries with easier environmental rules. The findings are confirmed by To et al. (2019), who indicated that FDI inflows frequently increase environmental degradation due to the absence of strong environmental regulations in the emerging Asian countries. However, the negative impact of the GDP–FDI interaction suggests that under certain conditions, such as technology spillovers and stricter governance, FDI inflow helps to support lower emissions with economic growth.

The positive link between income inequality and emissions is confirmed in the literature; the findings suggest that societies that lack resources experience uneven policy responses and unsatisfactory environmental issues. Ali's (2022) findings of Egypt supported our results; they demonstrated that income inequality causes an increase in long-run environmental degradation, which validates the political economy approach that suggests that it decreases the effectiveness of environmental regulations. Income inequality reduces the public demand for collective, environmentally friendly goods and increases the carbon footprint due to the usage of high-carbon products.

Energy poverty is a major element of emissions; emissions increase due to households' dependency on traditional polluting energy sources like firewood and kerosene. This suggests that the sig-

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nificant long-run structural energy deprivation prolongs the usage of the unsustainable energy over time. Mabogunje (2002) indicated that communities facing energy poverty issues are mostly physically situated in environmentally vulnerable zones and lack access to safe energy infrastructure, which increases both poverty and carbon emissions.

The interaction between poverty and GDP demonstrates that the environmental impact of economic growth is increased with poverty. This underlines the vulnerability of growth trajectories in Pakistan, where economic growth is not environmentally managed. Same findings are pointed out for the significant poverty–FDI interaction, which indicates that FDI inflow increases the ecological degradation due to weak environmental regulation or prioritisation of investment over environmental quality. Mabogunje (2002) indicated that globalisation and the race to attract foreign investment increase environmental concerns in low-income economies, which increases emissions.

The poverty and inequality interaction effect is statistically significant in the long run; this increases the environmental costs of social marginalisation. This increases the environmental issues. Our findings are consistent with the findings of Ali (2022), which indicate that income inequality weakens environmental governance and policy enforcement.

The significant energy poverty-GDP and energy poverty–FDI interaction terms reinforce the dispute that energy access reduces the environmental consequences of both economic growth and investment. It is observed that without a comprehensive clean energy infrastructure, economic activities rely on carbon-intensive systems, which causes an increase in environmental degradation. The energy poverty–income inequality interaction term indicates that the effects of increasing emissions, this reinforces the need for integrative policies for sustainability.

The negative and significant GDP–FDI interaction term indicates that when foreign investment is channelled with economic growth with robust governance, and modern infrastructure, it helps to reduce the environmental issues. This is due to the multinational corporations in moving cleaner technologies with adhering to global environmental standards to the host countries. To et al. (2019) indicated that this recognises the pollution halo effect, due to FDI supporting the green regulation and institutional capacity in host economies.

Dynamic ARDL Simulations Graphs

Figure 10 shows the dynamic response of environmental degradation to positive and negative economic growth shocks in Pakistan. The positive change reveals that a 10% increase in economic growth leads to an increase in environmental degradation, whereas a 10% decrease in economic growth helps improve environmental sustainability. This asymmetry highlights the environmental costs associated with rapid economic growth in the absence of green policies in Pakistan.

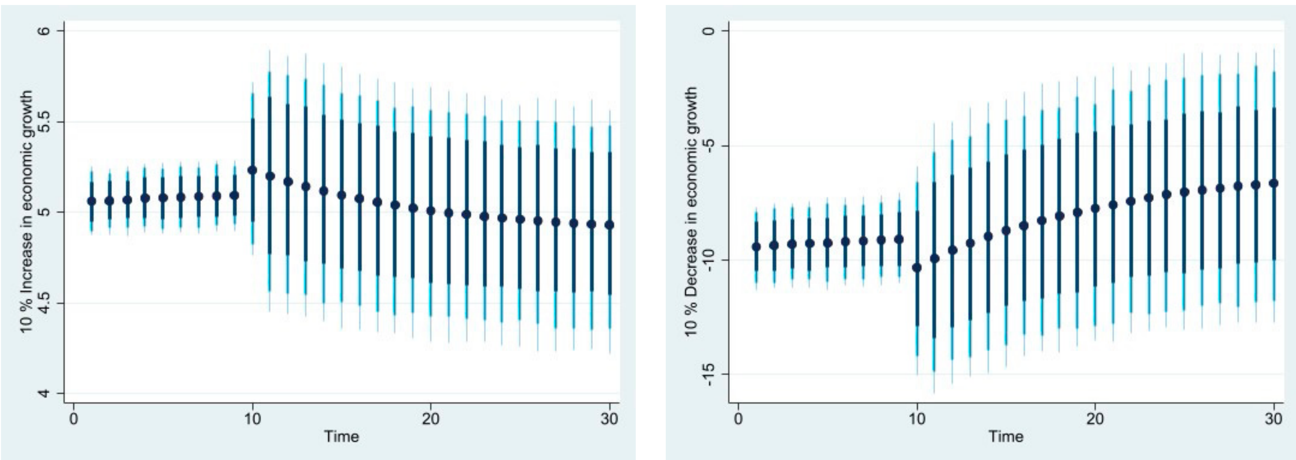

Figure 10. ± Shocks in Economic Growth

Figure 11 demonstrates the relationship between the squared term of economic growth and environmental degradation to verify the Environmental Kuznets Curve (EKC) hypothesis. The 10% increase in the squared value of GDP results indicates a decrease in carbon emissions, indicating that

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at higher levels of economic growth, issues improved. On the other hand, a 10% decrease in the squared GDP term causes an increase in emissions in both the short and long run. The results empirically verified the EKC hypothesis in Pakistan and recommended that sustainable development strategies become increasingly effective as the economy matures.

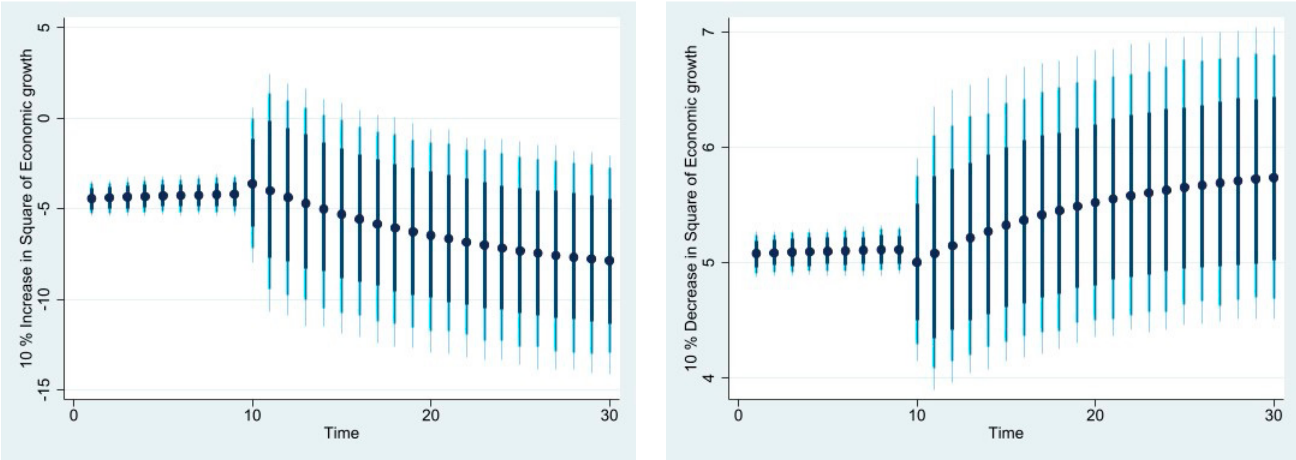

Figure. 11. ± Shocks in Square of Economic Growth

Figure 12 indicates the asymmetric impacts of the foreign direct investment (FDI) on environmental sustainability in Pakistan. A positive 10% increase in FDI is linked with improved environmental sustainability; however, a 10% reduction in FDI also appears to enhance environmental sustainability, both in the long and short run. Based on graphs of asymmetric relationships, FDI is an essential element in shaping environmental issues. Pakistan should focus on attracting environmentally responsible investments and implementing regulatory frameworks that ensure that FDI supports the SDGs.

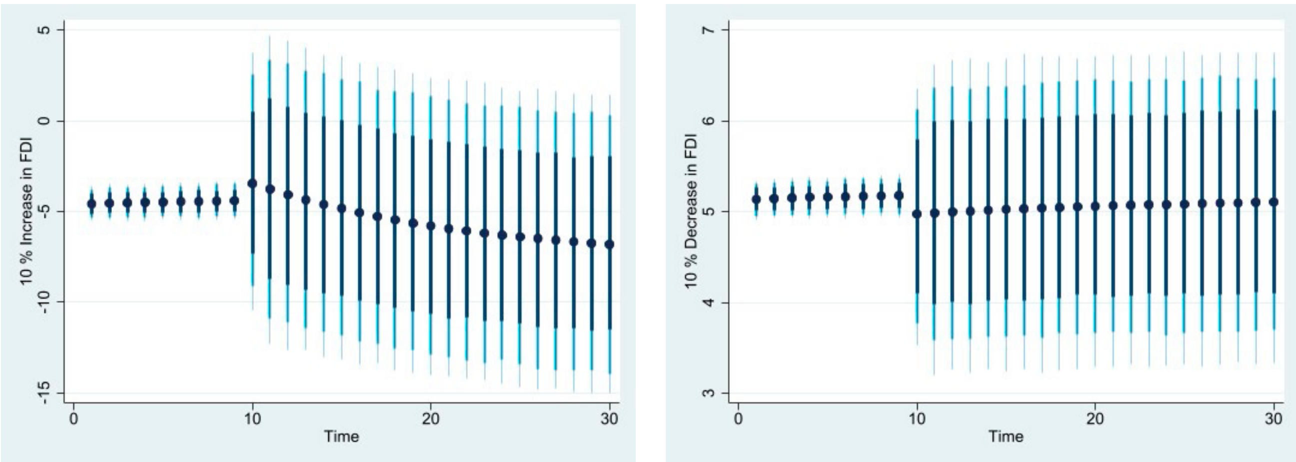

Figure 12. ± Shocks in Foreign Direct Investment

Figure 13 demonstrates the Pollution Haven Hypothesis (PHH) in Pakistan by asymmetric impacts of foreign direct investment (FDI) shocks on environmental degradation. A 10% positive increase in the squared value of FDI inflows helps decrease environmental sustainability, which verifies the PHH in Pakistan. On the other hand, a 10% decrease in the FDI square is linked with increased carbon dioxide emissions, demonstrating that the withdrawal or decline of environmentally responsible investments increases environmental issues. It is recommended to attract green and regulated FDI to mitigate emissions and to support long-term sustainability goals.

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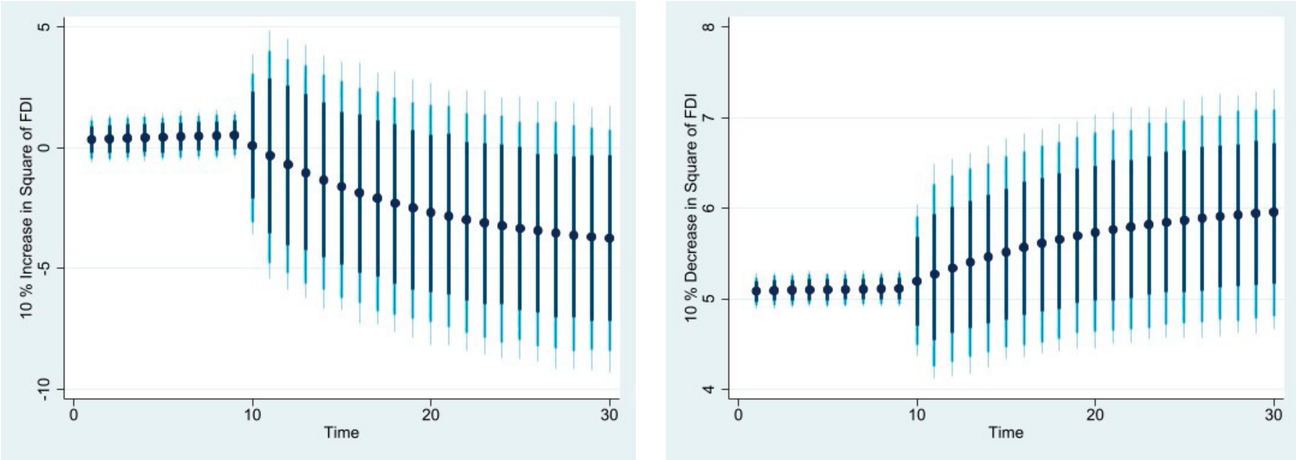

Figure 13. ± Shocks in Square of Foreign Direct Investment

Figure 14 demonstrates that a 10% increase in energy use is linked with environmental degradation, while a reduction in energy consumption helps reduce environmental issues. It is recommended that there be an urgent need for energy efficiency policies for cleaner energy sources to mitigate environmental degradation in Pakistan.

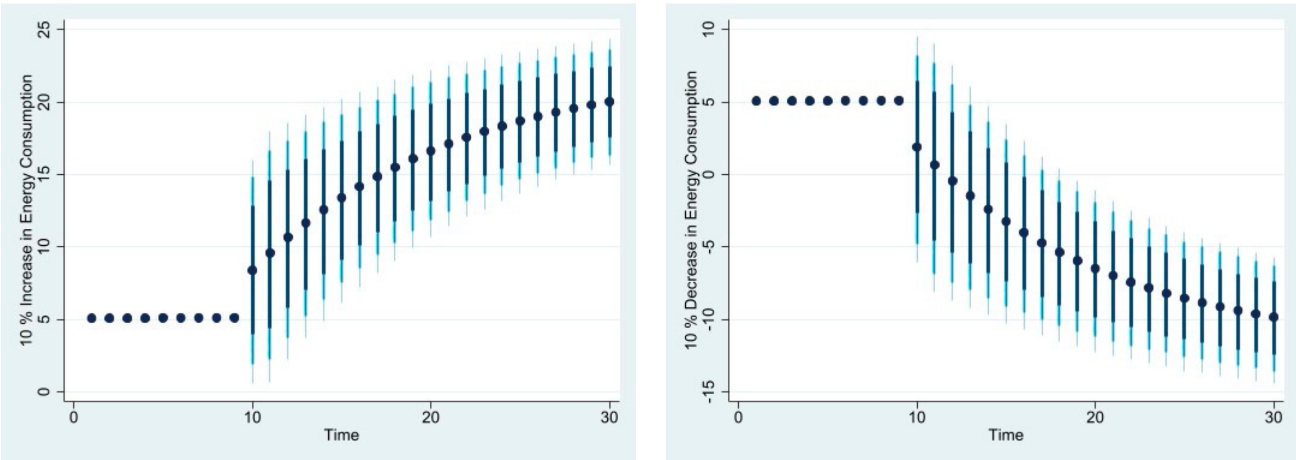

Figure 14. ± Shocks in Energy Consumption

Figure 15 shows the effect of energy poverty on environmental degradation in Pakistan. A 10% increase in energy poverty boosts environmental issues, whereas a reduction initially worsens degradation due to increased access to polluting energy sources in the long run.

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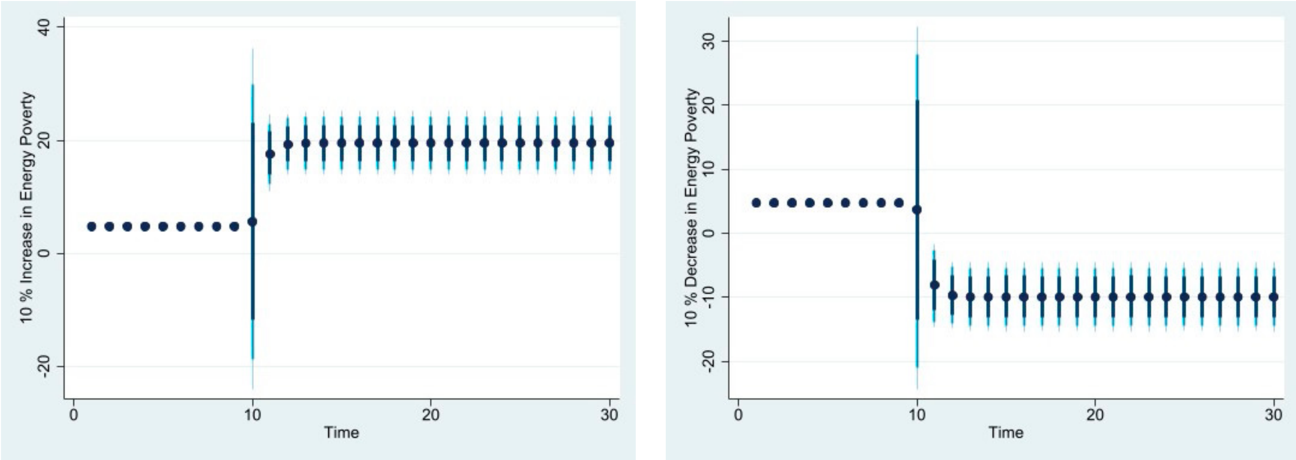

Figure 15. ± Shocks in Energy Poverty

Figure 16 shows the asymmetric effect of energy price shocks on environmental degradation in Pakistan. The first graph indicates that a 10% increase in energy prices helps reduce environmental degradation, whereas a decrease in energy prices increases environmental issues. Pricing policies play an essential role in promoting environmental sustainability and should be designed to discourage excessive energy consumption, particularly from non-renewable sources in Pakistan.

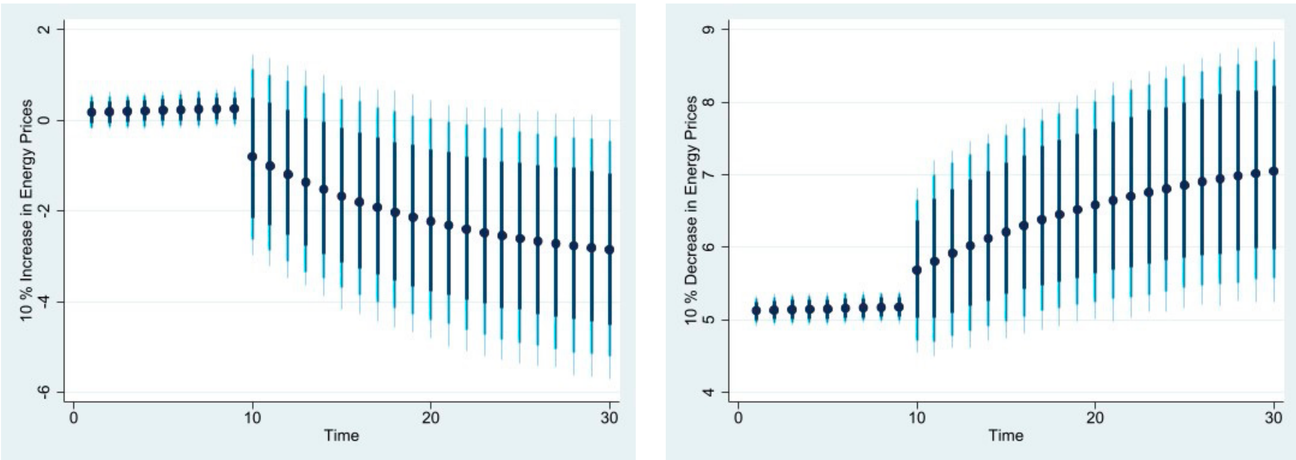

Figure 16. ± Shocks in Energy Prices

Figure 17 indicates the asymmetric effects of globalisation shocks on environmental degradation; a 10% positive shock in globalisation causes a reduction in environmental degradation, whereas a negative shock undermines environmental sustainability. Enhanced global integration can support environmental goals through effective governance and sustainable trade.

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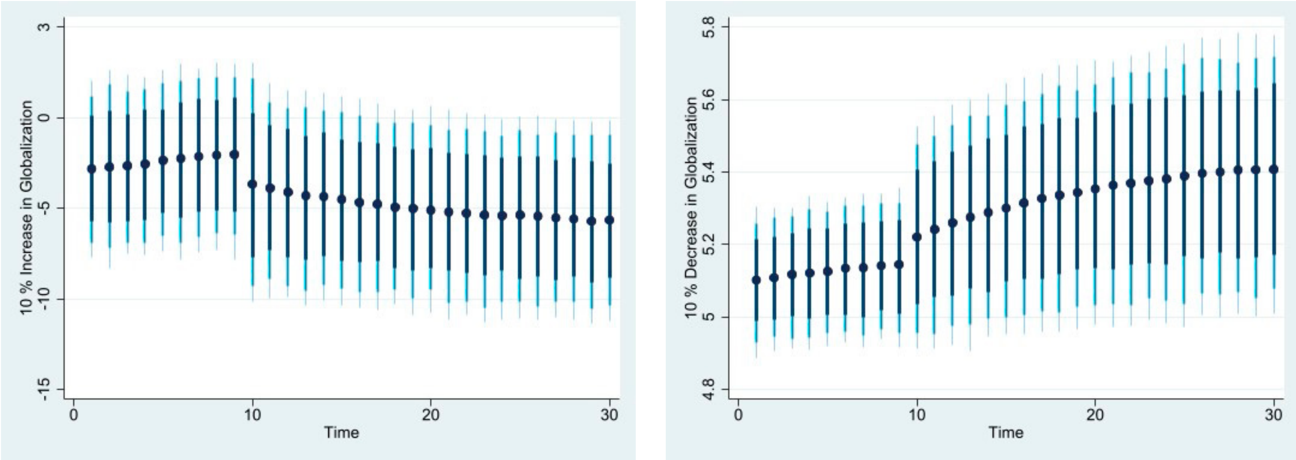

Figure 17. ± Shocks in Globalisation

Figure 18 shows the asymmetric impact of institutional quality shocks on environmental degradation in Pakistan. A 10% increase in institutional quality is associated with increased environmental degradation, while a decline appears to reduce it. The results reflect that institutional support for growth-oriented policies helps increase economic growth over environmental protection, underscoring the need for environmental considerations to be more deeply integrated into institutional frameworks in Pakistan.

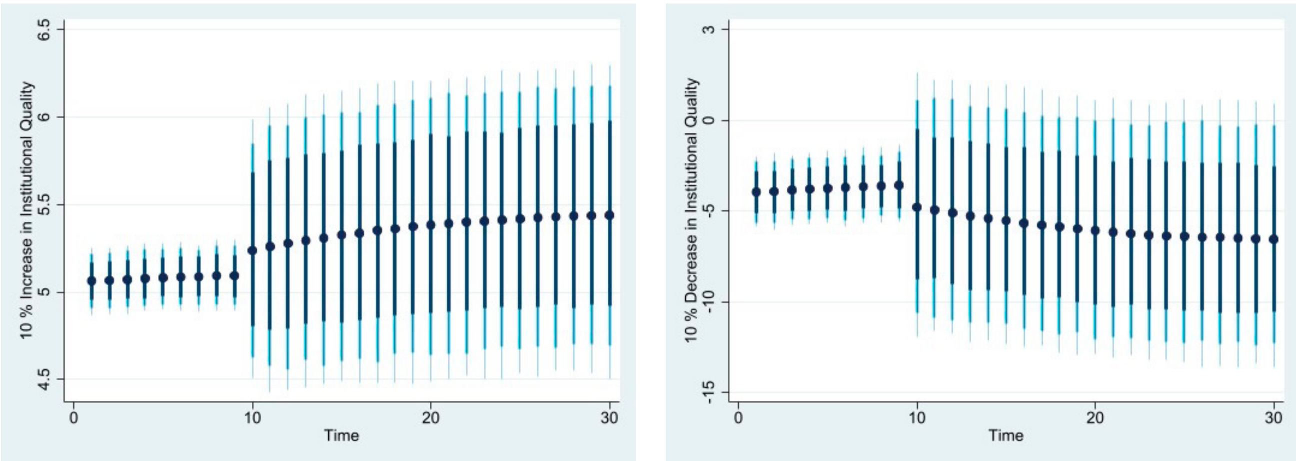

Figure 18. ± Shocks in Institutional Quality

Figure 19 shows the asymmetric effects of poverty shocks on environmental degradation in Pakistan. A 10% positive shock in poverty leads to increased environmental degradation, whereas a negative shock initially reduces environmental sustainability in Pakistan.

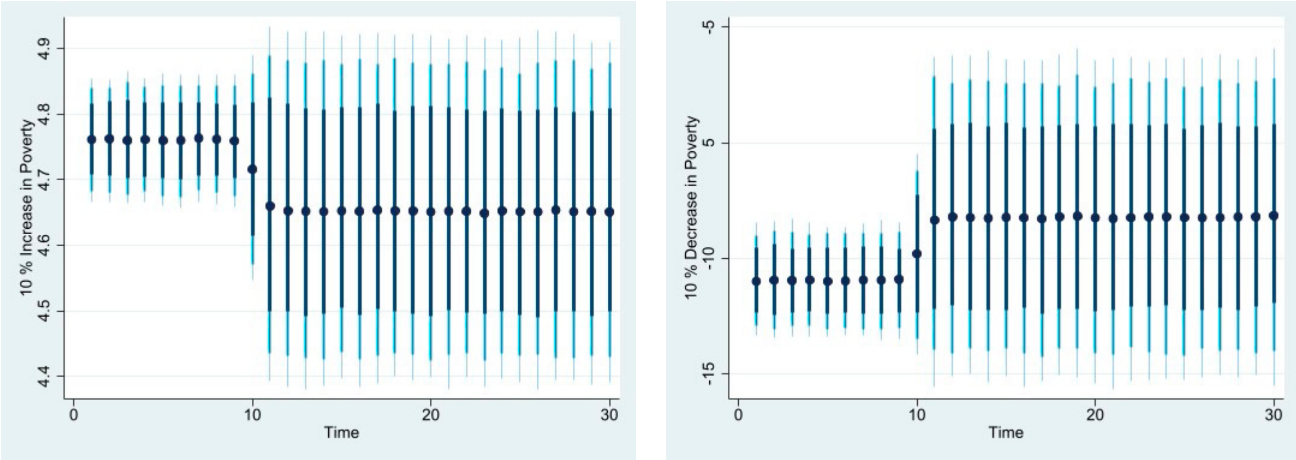

Figure 19. ± Shocks in Poverty

Figure 20 investigates the asymmetric impact of income inequality shocks on environmental sustainability in Pakistan. A 10% increase in income inequality reduces environmental sustainability, whereas a decrease initially shows a modest positive effect and ultimately leads to a reduction in environmental degradation over the long term. Based on these findings, we suggest that policies aimed at reducing income inequality can yield long-term environmental benefits, thus reinforcing the need for inclusive and equitable development strategies in Pakistan.

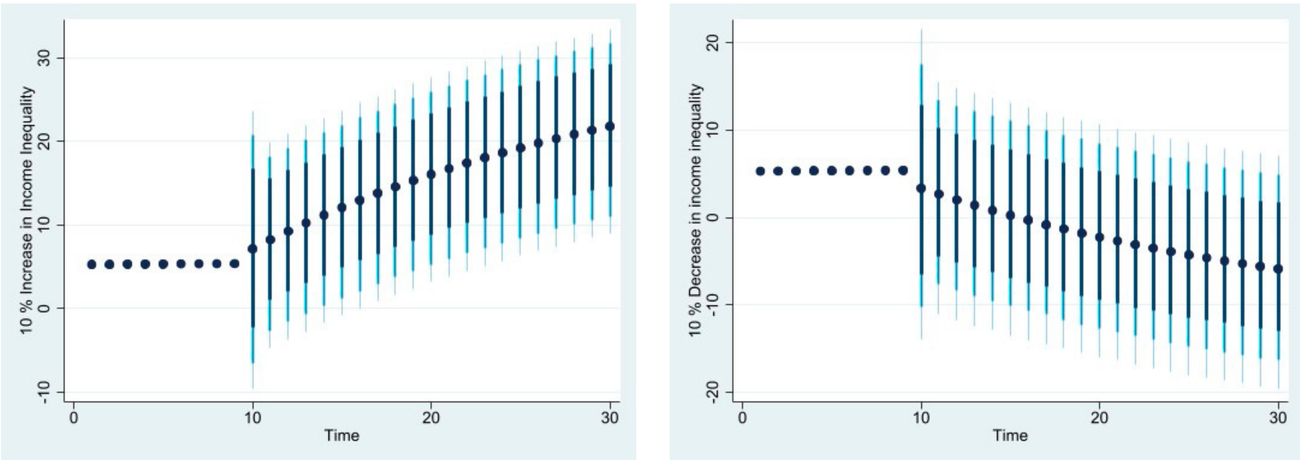

Figure 20. ± Shocks in Income Inequality

Conclusion and Policy Recommendations

This analysis examined the significant impact of various variables, such as energy poverty, poverty, income inequality, energy consumption, foreign direct investment (FDI) inflows, economic growth, institutional quality, and energy prices, on Pakistan's environmental degradation through the application of time series data. By relying on the advanced time series model, that is, the dynamic autoregressive distributed lag (ARDL) simulation model, in early research, traditional ARDL was mostly used again; however, in this study, we used the most recent model for results analysis. Further, this research verified the Environmental Kuznets Curve (EKC) hypothesis by checking the relationship between the square of economic growth and environmental degradation. This result indicates that environmental degradation initially increases with economic growth but eventually decreases as the economy matures, which verifies the Environmental Kuznets Curve (EKC) hypothesis. This research study verified the pollution haven hypothesis; the findings demonstrate the negative impact of squared FDI inflows on environmental degradation, confirming the pollution haven hypothesis.

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The findings reveal that energy poverty, globalisation, poverty, economic growth, FDI inflows, and income inequality in Pakistan worsen environmental degradation. On the other hand, the consumption of renewable energy and institutional quality play a mitigating role in environmental degradation. The results indicate that the interaction between poverty and economic growth has a positive but non-significant effect on the sustainability of the environment in Pakistan, while poverty interacts with FDI, which has a positive and statistically significant impact on carbon dioxide emissions. This study examined the interaction between energy poverty and income inequality, and the findings indicate a negative and significant influence on environmental degradation. Furthermore, the interaction of energy poverty with economic growth, FDI, and income inequality is examined, and the results indicate that energy poverty and economic growth positively and significantly impact carbon dioxide emissions, while energy poverty combined with FDI and income inequality negatively and significantly affect environmental degradation in Pakistan. The interaction between GDP and FDI shows a positive but nonsignificant effect on environmental degradation in Pakistan.

Recommendations

Achieving sustainable development goals is SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) in Pakistan by 2030 requires a strategic and integrated approach linking renewable energy initiatives, robust policy frameworks, and strong partnerships for a sustainable environment. Policy experts at the country level should focus on promoting solar and wind energy through subsidies, tax incentives, and low-interest loans, especially given Pakistan's favourable solar and wind resources. This suggests that the Government. The need to support hydropower projects at small and medium scales, mainly in the northern regions of Pakistan, is also important for a sustainable environment, and national energy efficiency standards should be introduced for the use of standard appliances for cooking, buildings, and industrial processes to manage energy demand effectively in Pakistan. Climate resilience must be strengthened through investments in climate-smart agriculture and disaster risk management, by introducing local and foreign investors. Pakistan must adopt policy and regulatory frameworks to develop an integrated energy policy that is aligned with climate goals to promote renewable energy projects. Introducing carbon pricing (taxes and revenue) can further drive industries to reduce the emissions that cause environmental degradation in Pakistan. Additionally, the implementation of environmental laws and the introduction of new regulations to prevent deforestation, pollution restrictions, and proper waste management are necessary for a sustainable environment. Finally, Govt. There is a need to establish centralised data systems to monitor and manage energy access, efficiency, and climate resilience for policy experts to predict future energy demand and supply. By implementing these strategies at the provincial and district levels, Pakistan can achieve its 2030 goals for a sustainable environment.

Limitations

This study gives useful insights but has some limits. First, it only uses time series data from Pakistan, so the results might not apply to other developing countries or regions. Second, the ARDL simulation model improves analysis, but the results can change based on the panel of countries. Third, the study does not look at specific sectors like transport, industry, or agriculture, which could help to understand emission sources better. Fourth, it examines interactions between energy poverty, FDI, and income inequality, but there might still be endogeneity issues. Also, the study focuses on statistical relationships and does not include qualitative or institutional data that could explain policy challenges.

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The contribution of the authors

Conceptualisation, M.K. Kh. and J.K. Ka; methodology, M.K. Kh.; validation, M.K. Kh.; formal analysis, M.K. Kh.; resources, M.K. Kh.; writing – original draft, M.K. Kh.; writing, review & editing, M.K. Kh.; visualisation, M.K. Kh.; supervision, J.K. Ka.; funding acquisition, R. B.

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Appendix

Energy Poverty Indicators

E1 Access to clean fuels and technologies for cooking (% of population)
E2 Access to clean fuels and technologies for cooking, rural (% of rural population)
E3 Access to clean fuels and technologies for cooking, urban (% of urban population)
E4 Access to electricity (% of population)
E5 Access to electricity, rural (% of rural population)
E6 Access to electricity, urban (% of urban population)

Globalisation Indicators

GB1 Financial Globalisation
GB2 Social Globalisation
GB3 Political Globalisation

Institutional Quality Indicators

IQ1 Control of Corruption
IQ2 Government Effectiveness
IQ3 Political Stability and Absence of Violence/Terrorism
IQ4 Regulatory Quality
IQ5 Rule of Law
IQ6 Voice and Accountability

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