



RESEARCH ARTICLE

Assessing Sustainability: A Comprehensive Analysis of Nuclear Energy, Energy Depletion, and Agriculture in Pakistan

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Abstract

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The pressing impacts of human activities on environmental sustainability made economists and environmentalists think about identifying indicators responsible for the degradation of environmental quality. Accordingly, this study brings a novel analysis adopting Pakistan's Load Capacity Factor (LCF) as the significant environmental sustainability indicator between 1990 and 2022 for empirical analysis. The study applied the novel Dynamic Autoregressive Distributed Lags (ARDL) framework and offered the policymakers compelling insights. It highlights the positive influence of nuclear energy on Pakistan's environmental sustainability by mitigating environmental degradation. In contrast, agriculture expansion and energy depletion remain contributing factors of environmental degradation in the country, signaling significant attention towards them. The results contributed to the fact that expansion in economic activities raises environmental deterioration in Pakistan. Kernel-based Regularized Least Squares (KRLS) was applied to re-affirm these findings. The outcomes obtained from the complex synergy between nuclear energy expansion, agriculture, and energy depletion with environmental sustainability make it critical to strengthen environmental quality by not harming the country's economic growth.

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Introduction

In the face of unprecedented global challenges related to climate change, resource scarcity, and environmental degradation, the quest for sustainability has become an imperative shared by nations across the world.¹ Pakistan, a rapidly developing South Asian nation with a burgeoning population, stands at a crucial juncture where the balance between economic growth and environmental preservation is of paramount importance.² This manuscript aims to shed light on Pakistan's pursuit of sustainability by meticulously evaluating three key facets: the role of nuclear energy in its energy matrix, the sustainability of its agriculture sector, and the looming threat of energy depletion. Pakistan's journey towards a sustainable energy future is intrinsically linked with its utilization of nuclear energy.³ In the past few decades, Pakistan has invested significantly in nuclear power generation to meet its rising energy demands. For example, Pakistan enhanced the capacity of its six nuclear reactors by adding 3530-megawatt electricity to the national grid.⁴ Understanding this nuclear energy adoption's environmental, economic, and social implications is essential.⁵ This manuscript will delve into the efficiency, safety, and environmental impact of nuclear power in Pakistan, offering a comprehensive evaluation of its contribution to the country's sustainability goals. Additionally, the manuscript will tackle the issue of energy depletion, which poses a grave threat to Pakistan's resource sustainability. Our economic prosperity heavily relies on energy sources primarily derived from the natural environment, notably older fossil fuels. When extracted and burned, these sources are the Earth's atmosphere and

¹ Atif Jahanger et al., "The Linkages between Natural Resources, Human Capital, Globalization, Economic Growth, Financial Development, and Ecological Footprint: The Moderating Role of Technological Innovations" *Resources Policy* 76 (June 2022): 102569, <https://doi.org/10.1016/J.RESOURPOL.2022.102569>.

² Boqiang Lin and Sami Ullah, "Effectiveness of Energy Depletion, Green Growth, and Technological Cooperation Grants on CO2 Emissions in Pakistan's Perspective" *Science of The Total Environment* 906 (January 2024): 167536, <https://doi.org/10.1016/J.SCITOTENV.2023.167536>.

³ Muhammad Tariq Majeed et al., "Evaluating the Asymmetric Effects of Nuclear Energy on Carbon Emissions in Pakistan" *Nuclear Engineering and Technology* 54, no. 5 (May 1, 2022): 1664–73, <https://doi.org/10.1016/J.NET.2021.11.021>.

⁴ Chuanwang Sun, Anwar Khan, and Sher Ali Kakar, "Pakistan's Safe Nuclear Energy Generation: An Essential Source to Target Sustainable Development" *Progress in Nuclear Energy* 164 (October 1, 2023): 104850, <https://doi.org/10.1016/J.PNUCENE.2023.104850>.

⁵ Mustafa Naimoğlu, "Exploring Nuclear Energy and Environment Interaction in Pakistan Using the Fourier ARDL" *Acta Montanistica Slovaca* 28 (September 19, 2023): 382–93, <https://doi.org/10.46544/AMS.v28i2.10>.

sustainability.^{6,7} According to the International Energy Agency⁸, global energy consumption has doubled over the past decade, with a 2.3% increase in fossil fuel demand. Electricity demand has surged by 50% as well.⁹ Developing countries, such as Pakistan, have experienced an increase in waste generation, resource extraction, fossil fuel consumption, and the expansion of their ecological footprint because of industrial and household growth. However, excessive utilization of ecosystem services, as seen with global warming, poses physical risks from environmental challenges.¹⁰ Pakistan, blessed with ample fossil fuel reserves, faces the challenge of balancing exploitation with ecological conservation, given that its fossil fuel era is nearing its end.¹¹ Lastly, agriculture, the backbone of Pakistan's economy, is another focal point in this analysis. The sustainability of Pakistan's agriculture sector is critical, not only for food security but also for economic and environmental well-being. Addressing these issues while shifting the energy sources from fossil-based to environmentally friendly is crucial, as continuing resource depletion is detrimental to the country's environmental sustainability.

Against these backdrops, the study formulates an empirical examination of nuclear energy, energy depletion and agriculture into environmental sustainability based on Pakistan's Load Capacity Factor (LCF). The "load capacity factor" of the environment refers to the ability of natural ecosystems to sustainably support the demands placed upon them by

⁶ Matthew Quayson et al., "Designing a Decision Support Tool for Integrating ESG into the Natural Resource Extraction Industry for Sustainable Development Using the Ordinal Priority Approach" *Resources Policy* 85 (August 1, 2023): 103988, <https://doi.org/10.1016/J.RESOURPOL.2023.103988.s>.

⁷ Atif Jahanger et al., "The Linkages between Natural Resources, Human Capital, Globalization, Economic Growth, Financial Development, and Ecological Footprint: The Moderating Role of Technological Innovations" *Resources Policy* 76 (June 1, 2022): 102569, <https://doi.org/10.1016/J.RESOURPOL.2022.102569>.

⁸ IEA, "Global Energy Demand Rose by 2.3% in 2018, Its Fastest Pace in the Last Decade" 2019, <https://www.iea.org/news/global-energy-demand-rose-by-23-in-2018-its-fastest-pace-in-the-last-decade>.

⁹ Elsa Barazza, Pei Hao Li, and Neil Strachan, "Modelling Governance for a Successful Electricity Sector Decarbonization" *Energy Research & Social Science* 104 (October 1, 2023): 103240, <https://doi.org/10.1016/J.ERSS.2023.103240>.

¹⁰ Jiapeng Dai et al., "Assessing the Nexus between Human Capital, Green Energy, and Load Capacity Factor: Policymaking for Achieving Sustainable Development Goals" *Gondwana Research*, April 25, 2023, <https://doi.org/10.1016/J.GR.2023.04.009>.

¹¹ Lin and Ullah, "Effectiveness of Energy Depletion, Green Growth, and Technological Cooperation Grants on CO2 Emissions in Pakistan's Perspective."

human activities, such as resource extraction and pollution. It quantifies the environmental load compared to the ecosystem's capacity, influencing the planet's overall sustainability.¹² Balancing these factors is crucial for long-term ecological health. This study's contributions are threefold: Firstly, it introduces nuclear energy's role in a comprehensive environmental indicator (LCF). Secondly, it explores the significance of energy depletion in Pakistan's environmental sustainability. Thirdly, it employs advanced econometric methods (including the dynamic ARDL as a benchmark estimator and KRLS as a robustness measure) to analyze the interplay between agriculture and the environment. These findings hold significant implications for shaping policies in Pakistan, particularly in the realms of environmental management, energy sustainability, and agricultural practices. The remaining study is structured as follows: Section two explains the Literature review, and the third section elaborates on "Data and Methods." The fourth section examines the significant findings and their discussion. Finally, conclude with a summary of the results and policy implications in the fifth section.

Literature review

This section overviews previous theoretical frameworks and empirical evidence regarding nuclear energy, energy depletion, agriculture, and environmental degradation. The first strand analyses the available literature on nuclear energy and its response to the environment. The second segment stretches the literature on energy depletion and the environment, while the third strand of the research explains the interplay between agriculture and environmental degradation.

Nuclear Energy and Environmental Degradation

Although there is limited research in this area, there is an increasing interest in the relationship between nuclear energy consumption and environmental sustainability. For example, Ref.¹³ conducted a study that investigated how nuclear energy affects environmental quality in 15 OECD countries. To explore this connection, they utilized advanced statistical techniques such as "Fully Modified OLS (FMOLS) and Vector Error Correction Model (VECM)". Their research revealed that nuclear energy has a beneficial impact in reducing pollution levels within these nations. Likewise, Ref.¹⁴

¹² Raúl Siche et al., "Convergence of Ecological Footprint and Energy Analysis as a Sustainability Indicator of Countries: Peru as Case Study" *Communications and Nonlinear Science and Numerical Simulation* 15, no. 10 (2010): 3182–92, <https://doi.org/10.1016/j.cnsns.2009.10.027>.

¹³ Kais Saidi and Anis Omri, "Reducing CO2 Emissions in OECD Countries: Do Renewable and Nuclear Energy Matter?" *Progress in Nuclear Energy* 126 (August 1, 2020): 103425, <https://doi.org/10.1016/J.PNUCENE.2020.103425>.

¹⁴ Mustafa Tevfik Kartal et al., "Effects of Possible Changes in Natural Gas, Nuclear, and Coal Energy Consumption on CO2 Emissions: Evidence from

investigated the role of energy consumption at disaggregated levels on the environment. These findings are also supported by Ref.¹⁵ for energy-importing countries. By applying dynamic Autoregressive Distributed Lag (DARDL) techniques, it was found that renewable energy sources like nuclear and hydro enhance environmental quality on the other hand, natural gas, coal, and oil consumption hinder environmental sustainability. Additionally, Ref.¹⁶ conducted an in-depth analysis of the connection between nuclear energy and CO₂ emissions within the leading countries that extensively utilised nuclear power from 1990 to 2017. They employed the Method of Moment Quantile Regression for their empirical investigations and concluded that nuclear energy represents a viable solution for reducing environmental pollution. In contrast, there have been scholars who have investigated the adverse effects of nuclear energy on the environment. For instance, a study conducted by Ref.¹⁷ found that nuclear energy did not lead to a reduction in consumption-based CO₂ emissions within the context of 15 OECD countries from 2005 to 2016. Further, in the empirical study of China, Ref.¹⁸, the panel countries discovered that nuclear energy positively correlated with environmental deterioration in these regions.

Energy Depletion and Environmental Degradation

In the field of energy research, the concept of energy security has emerged as a significant preoccupation for numerous nations, underscoring the significance of guaranteeing an adequate energy supply for all while also

France under Russia's Gas Supply Cuts by Dynamic ARDL Simulations Approach" *Applied Energy* 339 (June 1, 2023): 120983, <https://doi.org/10.1016/J.APENERGY.2023.120983>.

¹⁵ Mustafa Naimoğlu, "The Impact of Nuclear Energy Use, Energy Prices and Energy Imports on CO₂ Emissions: Evidence from Energy Importer Emerging Economies Which Use Nuclear Energy" *Journal of Cleaner Production* 373 (November 1, 2022): 133937, <https://doi.org/10.1016/J.JCLEPRO.2022.133937>.

¹⁶ Atif Jahanger et al., "Articulating CO₂ Emissions Limiting Roles of Nuclear Energy and ICT under the EKC Hypothesis: An Application of Non-Parametric MMQR Approach" *Geoscience Frontiers* 14, no. 5 (September 1, 2023): 101589, <https://doi.org/10.1016/J.GSF.2023.101589>.

¹⁷ Danish, Recep Ulucak, and Seyfettin Erdogan, "The Effect of Nuclear Energy on the Environment in the Context of Globalization: Consumption vs Production-Based CO₂ Emissions" *Nuclear Engineering and Technology* 54, no. 4 (2022): 1312–20, <https://doi.org/10.1016/j.net.2021.10.030>.

¹⁸ Arunava Bandyopadhyay et al., "The Role of Nuclear Energy Consumption in Abatement of Ecological Footprint: Novel Insights from Quantile-on-Quantile Regression" *Journal of Cleaner Production* 358 (July 2022): 132052, <https://doi.org/10.1016/J.JCLEPRO.2022.132052>.

safeguarding the environment.¹⁹ Overusing ecosystem services has reduced the regeneration capacity of our natural environment.²⁰ Due to the depletion of nonrenewable energy resources, fossil fuels are exploited and consumed more, which has severe environmental consequences. The study conducted by Ref.²¹ examined the impact of energy depletion on the environment using time series data from 1990 to 2020 for Pakistan. They utilized dynamic ARDL models for long-run estimation, uncovering that energy depletion has a detrimental impact on environmental quality. Similarly, Ref.²² investigated the dynamic linkages between CO₂ emissions and the energy depletion rate, discovering that the energy depletion rate hinders Thailand's environmental sustainability path. Additionally, investigations carried out by Ref.²³ delved into the inverse correlation between the depletion of natural resources and the state of the environment within a panel of countries participating in the Belt and Road Initiative (BRI). On the other hand, there is an indication of a positive connection between the depletion of energy resources and the quality of the environment. For instance, Ref.²⁴ narrated that Pakistan's energy depletion rate improves ecological quality. Furthermore, Ref.²⁵ conducted a study considering the role of energy depletion on environmental sustainability in the USA. For empirical conclusions, they utilized the novel and dynamic

¹⁹ Xing Yao et al., "The Impact of Trade on Energy Efficiency in the Global Value Chain: A Simultaneous Equation Approach" *Science of The Total Environment* 765 (April 2021): 142759, <https://doi.org/10.1016/J.SCITOTENV.2020.142759>.

²⁰ Samma Faiz Rasool et al., "Exploring the Role of Organizational Support, and Critical Success Factors on Renewable Energy Projects of Pakistan" *Energy* 243 (March 2022): 122765, <https://doi.org/10.1016/J.ENERGY.2021.122765>.

²¹ Lin and Ullah, "Effectiveness of Energy Depletion, Green Growth, and Technological Cooperation Grants on CO₂ Emissions in Pakistan's Perspective."

²² Kashif Raza Abbasi et al., "The Impact of Energy Depletion and Renewable Energy on CO₂ Emissions in Thailand: Fresh Evidence from the Novel Dynamic ARDL Simulation" *Renewable Energy* 180 (December 2021): 1439–50, <https://doi.org/10.1016/J.RENENE.2021.08.078>.

²³ Jamal Hussain, Anwar Khan, and Kui Zhou, "The Impact of Natural Resource Depletion on Energy Use and CO₂ Emission in Belt & Road Initiative Countries: A Cross-Country Analysis" *Energy* 199 (May 15, 2020): 117409, <https://doi.org/10.1016/J.ENERGY.2020.117409>.

²⁴ Sami Ullah, Songlin Tang, and Muhammad Yousaf Raza, "How the Energy Depletion Rate and Financial Structure Can Promote Environmental Sustainability: Empirical Evidence from Pakistan Using Ecological Footprints" *Energy Strategy Reviews* 50 (November 2023): 101208, <https://doi.org/10.1016/J.ESR.2023.101208>.

²⁵ Mohammad Razib Hossain et al., "Overcoming the Shock of Energy Depletion for Energy Policy? Tracing the Missing Link between Energy Depletion, Renewable Energy Development and Decarbonization in the US" *Energy Policy* 174 (March 2023): 113469, <https://doi.org/10.1016/J.ENPOL.2023.113469>.

ARDL techniques; their findings revealed that the energy depletion rate lowered the pollution rate from 1980 to 2019.

Agriculture and Environment

Similarly, the studies in previous literature focusing on the interplay between agriculture and environmental degradation based on CO₂ emissions and ecological footprints are enough now.^{26, 27} These studies similarly find that agriculture expansion raises environmental contamination in the long run. Similarly, Ref.²⁸ raised the concern that agriculture is a significant contributor of anthropogenic gases to the environment in Malaysia. The findings for Ghana obtained by Ref.²⁹ further disclosed that agriculture is detrimental to the environmental quality. Similar results have been identified by Ref.³⁰, which revealed that raising agriculture productivity consumes enormous amounts of fertilizers, which are subject to producing anthropogenic gases liable to deteriorate the environment in the long run. A further study by Ref.³¹ noted that a one per cent rise in farmland production tends to raise CO₂ emissions by 0.14% in the long run in China. However, we find a study which was conducted by Ref.³² reported a mitigating impact of agriculture on CO₂

²⁶ Lochan Kumar Batala et al., "The Implications of Forest Resources Depletion, Agricultural Expansion, and Financial Development on Energy Demand and Ecological Footprint in BRI Countries" *Clean Technologies and Environmental Policy* 1 (July 13, 2023): 1–17, <https://doi.org/10.1007/S10098-023-02575-3/TABLES/1>.

²⁷ Batala et al.; Junkai Qi et al., "Agricultural Productivity-Environmental Sustainability Nexus through the Lens of Digitalization and Energy Intensity in BRICS Countries" *Review of Development Economics*, 2023, <https://doi.org/10.1111/RODE.13045>.

²⁸ Asif Raihan et al., "Dynamic Impacts of Energy Use, Agricultural Land Expansion, and Deforestation on CO₂ Emissions in Malaysia" *Environmental and Ecological Statistics* 29, no. 3 (September 1, 2022): 477–507, <https://doi.org/10.1007/S10651-022-00532-9/METRICS>.

²⁹ Paul Adjei Kwakwa, Vera Acheampong, and Solomon Aboagye, "Does Agricultural Development Affect Environmental Quality? The Case of Carbon Dioxide Emission in Ghana" *Management of Environmental Quality: An International Journal* 33, no. 2 (February 21, 2022): 527–48, <https://doi.org/10.1108/MEQ-09-2021-0222/FULL/XML>.

³⁰ David Tilman, "Global Environmental Impacts of Agricultural Expansion: The Need for Sustainable and Efficient Practices" *Proceedings of the National Academy of Sciences* 96, no. 11 (May 25, 1999): 5995–6000, <https://doi.org/10.1073/PNAS.96.11.5995>.

³¹ Hongsheng Zhang et al., "Renewable Energy Utilization, Green Finance and Agricultural Land Expansion in China" *Resources Policy* 80 (January 1, 2023): 103163, <https://doi.org/10.1016/J.RESOURPOL.2022.103163>.

³² Asif Raihan, Said Ibrahim, and Dewan Ahmed Muhtasim, "Dynamic Impacts of Economic Growth, Energy Use, Tourism, and Agricultural Productivity on

emission. Hence, we hypothesize that the expansion of agriculture poses a considerable threat to the environment, necessitating the implementation of sustainable and conservation-oriented agricultural practices to mitigate these adverse effects.

Literature Gap

From the assessment of available literature, we know that the repercussions of nuclear energy, energy depletion, and agriculture on environmental sustainability based on load capacity factor (LCF) are unattended, and the gap remains. Therefore, assessing these variables to provide a policy guideline specifically in the context of Pakistan may bring consensus to build transparent energy, resources, agriculture, and environmental policies to build up an efficient paradigm for sustainable development. Therefore, an absence of research compels us to explore comprehensively the intricate interplay between nuclear energy, energy depletion and agriculture utilizing a comprehensive indicator of the environment, “The Load Capacity Factor”. Hence, investigating interdependencies and cumulative impact on sustainability, this research provides a more holistic understanding of the challenges and opportunities faced by Pakistan in its pursuit of environmental sustainability, thereby offering valuable insights for policymakers and researchers in the field.

Data and Methods

Data and Sources

This research aims to investigate the evolving interplay between nuclear energy, energy resource depletion, agricultural expansion, economic development, and environmental quality in Pakistan. This investigation utilizes the latest time series data from 1975 to 2022. To gauge environmental sustainability, we rely on the load capacity factor, calculated by dividing biocapacity by ecological footprint. Data concerning biocapacity and ecological footprints is sourced from the “Global Footprint Network.”³³ The nuclear energy data is measured in exajoules and taken from British Petroleum,³⁴ while the rest of the variable’s data is extracted from World Development Indicators.³⁵ To enhance the linearity among both dependent and independent variables and to normalize the skewed data, all parameters underwent a logarithmic transformation. Moreover, the details and definitions of the selected variables can be found in Table 1. Additionally, a trend

Carbon Dioxide Emissions in Egypt” *World Development Sustainability* 2 (June 1, 2023): 100059, <https://doi.org/10.1016/J.WDS.2023.100059>.

³³ GFN, “Global Footprint Network - Advancing the Science of Sustainability,” 2022.

³⁴ BP, “British Petroleum,” 2023.

³⁵ WDI, “World Bank Open Data | Data,” 2022.

analysis of these chosen variables has been presented in Figure 1. From the given trends, we may see that the environmental sustainability based on the LCF is declining over time, implying that economic activities consume natural resources.

Table 1. Details and Sources of Study Variables

Parameter s	Abbreviation	Unit	Source
Load Capacity Factor	LCF	Biocapacity (gha) ÷ ecological footprint(gha)	GFN
Nuclear Energy	Nuclear	Exajoules	British Petroleum
Energy Depletion	END	Energy depletion as Adjusted net savings in current US\$	WDI
Agriculture Expansion	RE	Value added Agriculture, including fishing and forestry as % of GDP	WDI
Economic Growth	GDP	Real Per capita GDP in 2015 US\$ constant	WDI

Note: gha indicates Global hectares per person, while GFN is Global Footprint Network. WDI is a World Development Indicators.

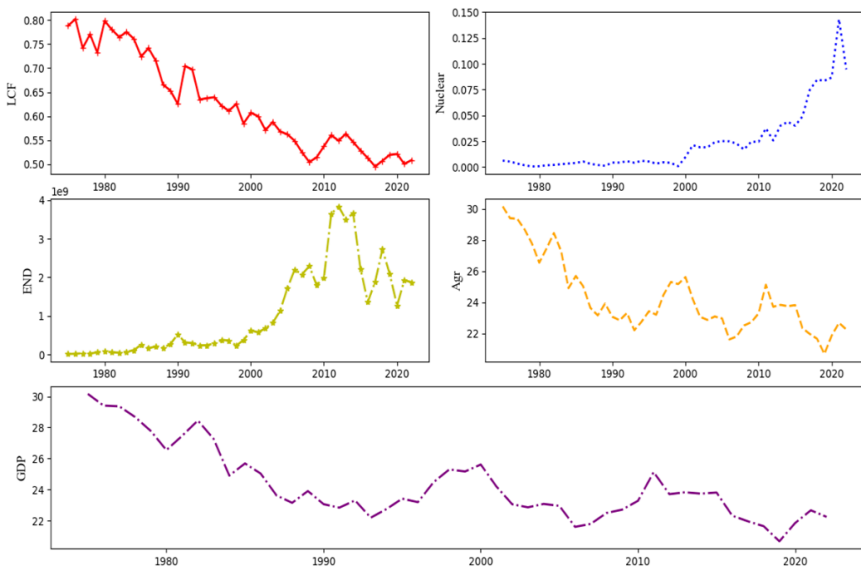


Figure 1. Trend analysis of all selected study variables

Model Construction & Methodology

The guiding general equation for encountering the effects of nuclear energy, energy depletion, agricultural expansion, and economic growth on the load capacity factor in time-series data can be expressed as follows:

$$LCF_t = \beta_0 + \beta_1 NUCLEAR_t + \beta_2 END_t + \beta_3 AGR_t + \beta_4 GDP_t + \Omega_t \quad (1)$$

Where the regressand LCF demonstrates the load capacity factor. The major regressors include nuclear energy (NUCLEAR), energy depletion (END), and agriculture expansion (AGR), simultaneously controlling for GDP, which signifies economic growth. Besides $\beta_1 - \beta_4$ displaying the long-run coefficients of the model, t is for periods and Ω_t is the disturbance term.

The current research scrutinizes the impacts of NUCLEAR, END, AGR, and GDP on environmental sustainability utilizing the unique “dynamic ARDL.” The methodological approach employed in this study delves into a range of multidimensional parameters over varying timeframes, addressing limitations present in the conventional ARDL model.³⁶ To examine the influence of explanatory variables on the dynamic response of the dependent variable, we utilized an innovative, dynamic ARDL simulation method. To execute the dynamic ARDL approach, the following steps were undertaken.

Estimation Strategy

1. The study applied the different stationarity tests before examining the long-run analysis, including the Phillip Perron (PP)³⁷, “Generalized Least Squared based Dickey Fuller” unit-root test (DF-GLS)³⁸, and Augmented Dickey-Fuller (ADF)³⁹ test. To conduct both ARDL and

³⁶ Lin and Ullah, “Effectiveness of Energy Depletion, Green Growth, and Technological Cooperation Grants on CO2 Emissions in Pakistan’s Perspective.”

³⁷ Peter C. B. Phillips and Pierre Perron, “Testing for a Unit Root in Time Series Regression” *Biometrika* 75, no. 2 (June 1988): 335, <https://doi.org/10.2307/2336182>.

³⁸ Dimitrios V. Vougas, “GLS Detrending and Unit Root Testing” *Economics Letters* 97, no. 3 (December 2007): 222–29, <https://doi.org/10.1016/J.ECONLET.2007.03.016>.

³⁹ David A. Dickey and Wayne A. Fuller, “Distribution of the Estimators for Autoregressive Time Series with a Unit Root” <https://doi.org/10.1080/01621459.1979.10482531> 74, no. 366 (2012): 427–31, <https://doi.org/10.1080/01621459.1979.10482531>.

DARDL analyses, the dependent variable must exhibit an integration order of $I(1)$, while the explanatory variables should demonstrate either $I(0)$ or $I(1)$. In the second stage, we determine the optimal lag length by employing various criteria such as “Hannan-Quinn Information Criteria (HQ), Adjusted R-squared, Schwarz Information Criteria (SIC), Final Prediction Error (FPE), and Akaike Information Criteria (AIC)”. This chosen lag length is subsequently employed to define the structure of the ARDL model.

2. After confirming a long-term cointegration relationship between the dependent variable and its chosen determinants, we employed different diagnostic tests to check for model specification, autocorrelation, heteroscedasticity, and normalcy of residuals. These diagnostics reveal and verify the validity and reproducibility of our model's results.
3. In the final step, we used a "Dynamic Autoregressive Distributed Lags (DARDL)" model to analyze the relationships between exogenous variables, considering both short and long-term effects. Unlike the complex conventional ARDL framework, the DARDL model has a simpler structure, making it easier to work with. Furthermore, the DARDL model provides a graphical representation of how the relationship between dependent and independent variables changes over time. This visual representation allows for evaluating the impact of each variable on the response variable while keeping other factors constant. For a detailed explanation of the estimation process, please refer to Figure 2.

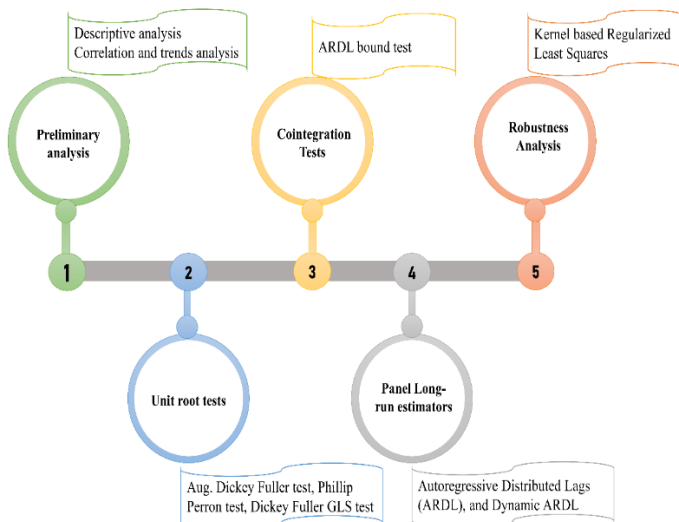


Fig. 2. Steps in estimation

Findings and Discussions

Descriptive Statistics

The first step of the analysis involved descriptive statistics, as shown in Table 2. LCF and NUCLEAR's derived mean of lagged values are non-positive, while END, AGR, and GDP's derived mean of lagged values are non-negative. The mean of END is the highest, while that of LCF is the lowest compared to the other variables. A kurtosis analysis reveals that LCF, NUCLEAR, END, AGR, and GDP have a lighter tail because their values are below the critical level. The skewness analysis revealed that all variables except END and GDP were left-skewed. The research represents Jarque-Bera test statistics for five variables: load capacity factor, nuclear energy, energy depletion, agricultural expansion, and economic growth. The p-values for all these variables are greater than 0.05, indicating that they are normally distributed. All these variables have p-values higher than 0.05, showing normal distribution.

Table 2. Descriptive Statistics

Descriptive statistics	LnLCF	LnNUCLEAR	LnEND	LnAGR	LnGDP
Mean	-0.4808	-4.6427	19.926	3.1846	6.8645
Minimum	-0.7028	-7.5207	16.5095	3.0291	6.377
Maximum	-0.2205	-1.9428	22.0681	3.4065	7.2956
St. Dv.	0.1545	1.4389	1.561	0.0917	0.2598
Skewness	0.2496	0.0161	-0.4737	0.8458	-0.124
Kurtosis	1.7053	2.0155	2.2377	2.8764	2.1459
Jarque-Bera	3.8512	1.9405	2.9573	5.7529	1.5819
Probability	0.1458	0.379	0.2279	0.0563	0.4534

In addition, Figure 3 illustrates multiple pieces of information in the data. For example, the upper triangle explains the Pearson correlation coefficients at a 5% level. Similarly, the lower triangle of the data plots with trend lines. At the same time, the diagonals of the figure explain the data distribution by plotting the individual histograms of the series. From the information on the correlation relationship between the variables, the correlation coefficient between -1 and +1 signals a positive (negative) correlation between the variables. There is a one-to-one relationship when the correlation is close to +1 or -1. Figure 3 shows that LCF is negatively correlated with NUCLEAR, END, and GDP, whereas LCF is positively correlated with AGR. Pearson correlation coefficient results indicate a

statistically significant correlation between all variables. A strong relationship between LCF, NUCLEAR, END, AGR, and GDP is evident. The lower left triangle of Figure 3 also shows a scatter plot of two variables. This section describes the magnitude and direction of the relationship. Thus, LCF decreases with increasing NUCLEAR, END, and GDP, but the relationship is reversed with increasing AGR. Figure 3 illustrates the distribution characteristics of those variables using diagonal graphs.

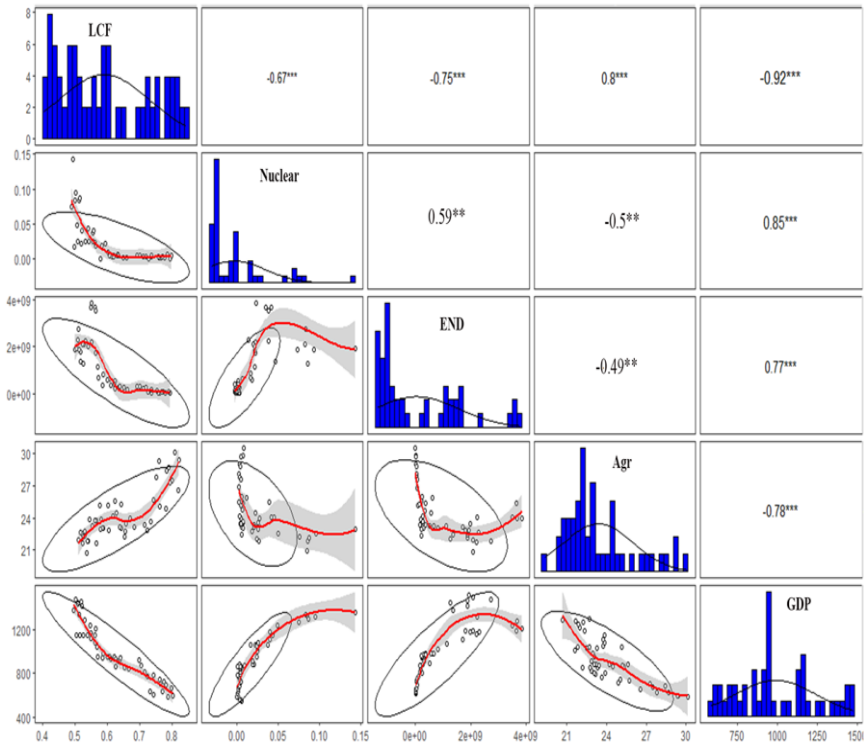


Figure 3. Graphically presentation of the correlation structure

Unit Root Test

Following our initial assessment, we conducted stationarity tests using the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Dickey-Fuller Generalized Least Squares (DF-GLS) methods. Table 3 presents the results of these tests, which were performed at the variables' levels and their first differences. Notably, at the level of the variables, none of them exhibited statistically significant t-statistics at the 5% significance level. This suggests that the unit-roots of all these variables render them non-stationary. However, when the tests were applied to the first differences of the variables, all variables displayed statistically significant t-statistics at the 5% significance level. These results indicate that all the variables possess an order of

integration I (1), signifying that they are integrated of order one and require differencing to achieve stationarity.

Table 3. Results of unit root tests

Variables	Augmented Dickey-Fuller (ADF)		Phillip Perron (PP)		DF- GLS Residuals	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
LnLCF	-1.1682	-8.6956	-0.9841	-11.0536	-0.2345	-7.7436
	(0.6805/ /2.925)	(0.000/ 2.926)	(0.751/ -2.925)	(0.000/ -2.926)	(-1.947)	(-1.948)
LnNUCLEA R	-0.9968	-7.4092	-0.7923	-8.0728	-1.0052	-7.1296
	(0.747/ -2.925)	(0.000/ -2.926)	(0.812/ -2.925)	(0.000/ -2.926)	(-1.947)	(-1.948)
LnEND	-2.1404	-6.9552	-2.9273	-7.0532	-0.2849	-6.9615
	(0.230/ -2.925)	(0.000/ -2.926)	(0.049/ -2.925)	(0.000/ -2.926)	(-1.948)	(-1.948)
LnAGR	-2.4262	-6.7051	-2.4199	-6.705	-0.8195	-6.4013
	(0.140/ -2.926)	(0.000/ -2.928)	(0.142/ -2.925)	(0.000/ -2.926)	(-1.948)	(-1.948)
LnGDP	-1.3855	-5.642	-1.2728	-5.8234	0.5818	-5.6354
	(0.581/ -2.925)	(0.000/ -2.926)	(0.634/ -2.925)	(0.000/ -2.926)	(-1.948)	(-1.948)

Note: (t-stats/p-scores)

Lag Selection Criteria

Selecting an optimal lag length for the variables is required to evaluate the long-run connections between the variables. Therefore, based on likelihood ratios (LR), Akaike (AIC), log-likelihoods (LL), Schwarz Bayesian information criteria (SBC), Hannan-Quinn (HQ), and final prediction error (FPE), optimal lag lengths (one lag) are determined for examining the variables for long-run analysis. The results of these methods are summarized in Table 4. We chose one optimal lag length using the statistics from most of the tests.

Table 4. Selection of Optimal Lags

Lags	LogL	FPE	AIC	SC	LR	HQ
0	84.07	1.90E-08	-3.59409	-3.5189		-3.39134
1	250.00 3	3.2e-11*	- 10.0002*	- 9.54902*	331.87	- 8.78366*
2	267.96	4.50E-11	-9.68001	-8.85293	35.914	-7.44977
3	289.95 4	5.90E-11	-9.54337	-8.34035	43.988	-6.29939
4	308.78 2	1.00E-10	-9.26281	-7.68384	37.655 *	-5.00509

Bound Test

We performed a long-term cointegration bound test employing the KS critical value, and the outcomes have been outlined in Table 5. At a 5% significance level, the p-value is linked to the null hypothesis, which posits that the variables are not cointegrated. The results reject the null hypothesis, consequently, the data indicates the presence of long-term relationships among the variables, underscoring the need for a more in-depth investigation of these associations.

Table 5. Bound Test

K		1%		5%		10%		p-value	
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
F	6.41 3	2.62 9	3.82 8	3.17	4.51 3	2.62 9	3.82 8	0.00 3	0.01 3
t	- 6.02 5	-2.55	- 3.65 8	- 2.89 3	-4.06	-2.55	-3.66	0	0.00 8

Note: I(0) and I(1) indicate lower and upper bounds. Decision rule: $F/T > I(1)$, cointegration exists in the model.

Long Run Estimates

The outcomes of ARDL and DARDL, p-values, and standard errors are given in Table 6. The findings of both estimation techniques signify that nuclear energy exhibits a positive association with the load capacity factor, indicating that nuclear energy boosts environmental sustainability in Pakistan. According to findings, a 1% surge in NUCLEAR causes a 0.16% rise in

environmental quality. These results corroborate the previous studies.^{40,41} There are multiple reasons for this result. A significant benefit of nuclear energy technology is that it has been proven to be a reliable and established method of generating electricity for a long time.⁴² Moreover, it does not deplete over time or emit any emissions.⁴³ Additionally, nuclear energy reduces fossil fuel use, benefiting the environmental quality. Secondly, nuclear energy can meet the growing energy demand and reduce the dependence on fossil fuel imports. The third significant development is after acquiring Pakistan's first nuclear power plant from Canada, Pakistan currently generates approximately 8% of its electricity from nuclear power plants. By 2030, Pakistan intends to increase this figure to 20 per cent.⁴⁴ Contrary to this, the END coefficient negatively correlates with the load capacity factor, implying that the energy depletion rate hinders environmental sustainability in Pakistan. The study findings are similar to the prior work.^{45,46} As an example, Pakistan heavily depends on fossil fuels, particularly coal and oil, to satisfy its energy requirements.⁴⁷ Apart from depleting finite resources, the combustion of fossil fuels emits substantial quantities of CO₂ into the atmosphere, thus contributing to global warming.⁴⁸ Furthermore, Pakistan's energy infrastructure is antiquated and inefficient, leading to elevated energy

⁴⁰ Sun, Khan, and Kakar, "Pakistan's Safe Nuclear Energy Generation: An Essential Source to Target Sustainable Development."

⁴¹ Majeed et al., "Evaluating the Asymmetric Effects of Nuclear Energy on Carbon Emissions in Pakistan."

⁴² Anwar Khan and Chuanwang Sun, "The Asymmetric Nexus of Energy-Growth and CO₂ Emissions: An Empirical Evidence Based on Hidden Cointegration Analysis" *Gondwana Research*, July 24, 2023, <https://doi.org/10.1016/J.GR.2023.07.012>.

⁴³ Muhammad Amir Raza, Krishan Lal Khatri, and Arslan Hussain, "Transition from Fossilized to Defossilized Energy System in Pakistan" *Renewable Energy* 190 (May 1, 2022): 19–29, <https://doi.org/10.1016/j.renene.2022.03.059>.

⁴⁴ Nasir Mahmood et al., "The Role of Nuclear Energy in the Correction of Environmental Pollution: Evidence from Pakistan" *Nuclear Engineering and Technology* 52, no. 6 (June 2020): 1327–33, <https://doi.org/10.1016/J.NET.2019.11.027>.

⁴⁵ Lin and Ullah, "Effectiveness of Energy Depletion, Green Growth, and Technological Cooperation Grants on CO₂ Emissions in Pakistan's Perspective."

⁴⁶ Lin and Ullah; Ullah, Tang, and Yousaf Raza, "How the Energy Depletion Rate and Financial Structure Can Promote Environmental Sustainability: Empirical Evidence from Pakistan Using Ecological Footprints."

⁴⁷ Rasool et al., "Exploring the Role of Organizational Support, and Critical Success Factors on Renewable Energy Projects of Pakistan."

⁴⁸ Boqiang Lin, Runqing Zhu, and Muhammad Yousaf Raza, "Fuel Substitution and Environmental Sustainability in India: Perspectives of Technical Progress" *Energy* 261 (December 2022): 125309, <https://doi.org/10.1016/J.ENERGY.2022.125309>.

consumption and waste. The lack of efficiency in both power plants and transmission systems plays a role in energy depletion and the escalation of CO₂ emissions.⁴⁹ Similarly, the study revealed that AGR negatively correlates with the load capacity factor. It shows that a 1% rise in AGR is responsible for a 0.04% dwindling in environmental quality. These discoveries align with the empirical work of Ref.⁵⁰ India's case, unveiling that agricultural expansion has triggered environmental pollution in these regions. Additionally, the study indicates that a 1% increase in economic growth leads to environmental contamination by 0.11% in the long run. The reason for this negative impact of economic growth on the environment is that the growing economies tend to generate more pollution from the use of equipment, particularly in the industrial sector, resulting in environmental degradation over the long term.⁵¹ Moreover, we conducted a series of diagnostic tests to assess the reliability and stability of the ARDL coefficients. The comprehensive diagnostic results are in Table 7 for a more detailed examination.

Counterfactual Analysis of Variables

DARDL can predict, simulate, and estimate graphs. In summary, DARDL is a tool that can model and predict the effects of changes in specific variables (NUCLEAR, END, AGR, and GDP) on long-term environmental and economic sustainability, and the results are visualized in Figures 4-7. The interpretation of these figures suggests that changes in these variables have varying impacts on the environment and long-term sustainability. From Figure 4, a 10% positive change in the NUCLEAR variable is predicted to benefit the environment. In contrast, a 10% unfavorable change in NUCLEAR is predicted to have an adverse effect on the environment. Figure 5 illustrates that a positive change of 10% in the END variable is expected to lead to environmental pollution. Conversely, a negative change of 10% in END is predicted to increase LCF in the long run. Figures 6 and 7 disclose that the prediction outcomes for variables like AGR and GDP seem similar to

⁴⁹ Qamar Ali et al., "The Impact of Tourism, Renewable Energy, and Economic Growth on Ecological Footprint and Natural Resources: A Panel Data Analysis" *Resources Policy* 74 (December 2021): 102365, <https://doi.org/10.1016/J.RESOURPOL.2021.102365>.

⁵⁰ Md Shabbir Alam et al., "The Impacts of Globalization, Renewable Energy, and Agriculture on CO₂ Emissions in India: Contextual Evidence Using a Novel Composite Carbon Emission-Related Atmospheric Quality Index" *Gondwana Research* 119 (July 2023): 384–401, <https://doi.org/10.1016/J.GR.2023.04.005>.

⁵¹ Boqiang Lin and Sami Ullah, "Towards the Goal of Going Green: Do Green Growth and Innovation Matter for Environmental Sustainability in Pakistan" *Energy*, October 2023, 129263, <https://doi.org/10.1016/J.ENERGY.2023.129263>.

the END variable in their impact on LCF. These results are presented in Figures 6 and 7, respectively.

Table 6. Long Run Estimates

Variables	Autoregressive Distributed Lags			Dynamic ARDL (DARDL)		
	Estimate s	SE	p-value	Estimate s	SE	p-value
LnLCF _{t-1} (ECT _{t-1})	-0.437	0.119	0.001	-0.398	0.114	0.001
<i>Long-run</i>						
LnNUCLEAR _{t-1}	0.039	0.016	0.018	0.166	0.069	0.021
LnEND _{t-1}	-0.054	0.025	0.040	-0.027	0.013	0.044
LnAGR _{t-1}	-0.054	0.025	0.040	-0.041	0.016	0.015
LnGDP _{t-1}	-0.370	0.205	0.079	-0.116	0.035	0.002
<i>Short-run</i>						
ΔLnNUCLEAR	0.019	0.010	0.072	0.181	0.067	0.010
ΔLnEND	-0.038	0.016	0.020	-0.036	0.015	0.022
ΔLnAGR	-0.265	0.098	0.010	-0.025	0.011	0.031
ΔLnGDP	-0.021	0.012	0.079	-0.015	0.008	0.056
Obser.	47	R ²	0.916		R ²	0.857

Note: SE indicates standard errors, and the p-value is the probability score. R² is the coefficient of determination.

Table 7. Diagnostics tests

Checks	p-value (X ²)	Decision
Breusch-Godfrey LM	0.49	Residual not serially correlated
Breusch-Pagan-Godfrey	0.67	Homoscedasticity
Ramsey RESET test	0.68	Model specified correctly
Jarque-Bera test	0.76	Normalcy of residuals

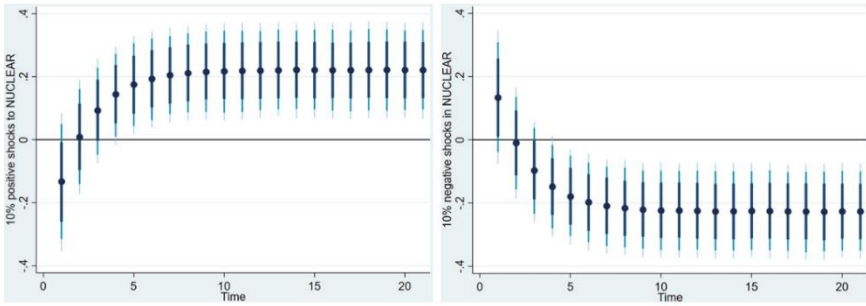


Figure 4. Positive and Negative Shock's Impact of NUCLEAR on LCF

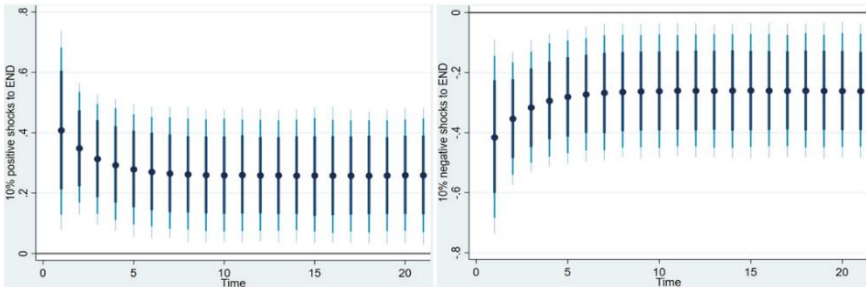


Figure 5. Positive and negative shock impact of END on LCF

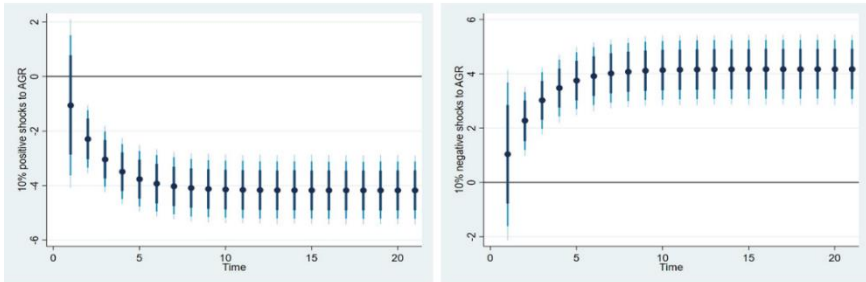


Figure 6. Positive and negative shock impact of AGR on LCF

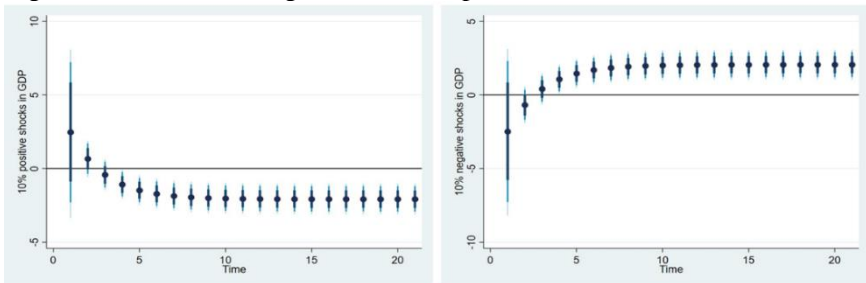


Figure 7. Positive and negative shock impact of AGR on LCF
Robustness of the Results

To ensure the consistency and robustness of our findings, we employed a machine-learning technique known as Kernel Regularized Least Square (KRLS).^{52,53} Compared to other machine-learning methods, KRLS offers the advantage of flexible and interpretable parameters. Additionally, this approach minimizes the potential for variation and susceptibility to different adjustments.^{54, 55} The results of the KRLS analysis are presented in Table 8. They reveal that nuclear energy (NUCLEAR) positively impacts LCF, while energy depletion (END), agriculture and GDP exhibit negative correlations with LCF. These results align with the patterns observed in the ARDL and DARDL approaches for most variables, except for agriculture expansion (AGR), where the coefficient is statistically insignificant.

Table 8. Robustness with KRLS

LnLCF	Average	St.Er	t-stats	p > t	P25	P50	P75
LnNUCLEAR	0.014	0.006	2.161	0.036	0.005	0.012	0.020
LnEND	-0.024	0.008	-2.980	0.005	-0.053	-0.024	0.000
LnAGR	-0.020	0.082	-0.240	0.813	-0.205	0.062	0.238
LnGDP	-0.339	0.047	-7.240	0.000	-0.529	-0.353	-0.186
<i>Checks</i>							
Lambda	0.093	Sigma	4	R ²	0.974	Obse	48
Tolerance	0.048	Eff. Df	15.990	Loolos	0.406		

⁵² Jeremy Ferwerda, Jens Hainmueller, and Chad J. Hazlett, “Kernel-Based Regularized Least Squares in R (KRLS) and Stata (KRLS)” *Journal of Statistical Software* 79, no. 3 (2017): 1–26, <https://doi.org/10.18637/JSS.V079.I03>.

⁵³ Samuel Asumadu Sarkodie and Phebe Asantewaa Owusu, “How to Apply the Novel Dynamic ARDL Simulations (Dynardl) and Kernel-Based Regularized Least Squares (Krls)” *MethodsX* 7 (January 1, 2020): 101160, <https://doi.org/10.1016/J.MEX.2020.101160>.

⁵⁴ Mustafa Tevfik Kartal, “Production-Based Disaggregated Analysis of Energy Consumption and CO2 Emission Nexus: Evidence from the USA by Novel Dynamic ARDL Simulation Approach” *Environmental Science and Pollution Research* 30, no. 3 (January 2023): 6864–74, <https://doi.org/10.1007/S11356-022-22714-5/TABLES/9>.

⁵⁵ Ferwerda, Hainmueller, and Hazlett, “Kernel-Based Regularized Least Squares in R (KRLS) and Stata (KRLS).”

Note: St. Er. indicates standard errors, and p is the probability score. R^2 is the coefficient of determination.

Conclusions and Policy Implications

The main objective of this research was to establish the intricate connections between environmental sustainability, nuclear energy, and energy depletion while considering factors such as agricultural expansion and economic growth. Pakistan's economy has been experiencing rapid growth, primarily driven by the extensive use of fossil fuels, significantly impacting climate change. Many nations face challenges shifting from fossil fuels to cleaner, more environmentally friendly energy sources. Pakistan needs to make this transition to safeguard the global environment. Understanding the reasons and mechanisms behind this transition is paramount for policymakers, think tanks, and researchers to ensure positive environmental benefits. In pursuit of this objective, the study delved into the adverse consequences of the excessive use of ecological resources within the context of nuclear energy and agricultural expansion. More specifically, the research aimed to explore the relationships between LCF (environmental sustainability), nuclear energy (NUCLEAR), energy depletion (END), agricultural expansion (AGR), and GDP (economic growth). The study employed time series data from 1975 to 2022 and various econometric techniques to ensure consistent and dependable results. The final modelling used the Dynamic Autoregressive Distributed Lag (ARDL) model, chosen for its advantages over traditional ARDL. Additionally, Kernel Regularized Least Squares (KRLS) was used to enhance the accuracy of the study's findings. Through the application of these methodologies, the study provided evidence that nuclear energy positively contributes to environmental sustainability, while energy depletion (END), agricultural expansion (AGR), and economic growth (GDP) have adverse effects on it. Additionally, it was observed that the variable LCF exhibited significant changes in response to both positive and negative shocks related to NUCLEAR, END, AGR, and GDP.

Several policy recommendations can be formulated based on the empirical findings presented in this study. For example, the finding that nuclear energy enhances environmental sustainability in Pakistan carries profound policy implications. To leverage this result, policymakers should prioritize expanding nuclear energy infrastructure through supportive regulations, incentives, and investment. Rigorous safety measures and public awareness campaigns are essential to ensure safe and responsible nuclear energy utilization. Simultaneously, investment in research and development should be encouraged to enhance the efficiency and safety of nuclear technology. Collaborating with international partners and diversifying the energy mix with renewables can provide a balanced and secure energy future. By adopting these measures, Pakistan can reduce its reliance on fossil fuels, mitigate environmental degradation, and pave the way for a sustainable

energy landscape while promoting economic growth and energy security. The revelation that energy depletion and agriculture expansion diminish environmental sustainability in Pakistan necessitates immediate policy action. Policymakers should address these issues by implementing measures to reduce energy depletion through energy efficiency programs, encouraging the responsible use of energy resources, and investing in renewable energy sources to curb environmental impact. In the context of agriculture expansion, sustainable farming practices should be promoted, emphasizing efficient land and water resource management, reduced pesticide and fertilizer usage, and reforestation to counteract deforestation.

Furthermore, Pakistan's heavy reliance on costly and environmentally damaging fossil fuels, mainly imported petroleum products, is a significant issue. To address this, Pakistan should prioritize environmentally friendly and cost-effective energy sources like nuclear, solar, wind, and hydropower. Effective governance and management are crucial to ensure the affordability and sustainability of these alternatives. Additionally, Pakistan needs to invest in green technologies and cleaner energy solutions, including low-carbon technologies. This approach can boost economic growth and environmental sustainability. To integrate renewable energy sources seamlessly, policymakers should focus on long-term energy infrastructure planning. By promoting nuclear energy, wind, solar, and hydroelectric power, the government can reduce dependence on imports and enhance energy security, leading Pakistan towards a more sustainable and self-reliant energy future. While containing rigorous analysis and concluding with efficient findings, this study still opens multiple avenues for future research. This research can be extended by employing nuclear energy and its effective usage in Pakistan's agriculture and health industries. It may enhance understanding of safe nuclear applications and their environmental and economic advantages across the country. Similarly, the long-time series has multiple issues, including the spillover effects; future research may be conducted by accounting for structural breaks and spillover effects of energy shocks in the country.