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Urbanization, Energy Use, and CO_2 Emissions in Pakistan: A Time-Series Analysis

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ABSTRACT

The last decades have become the years of urbanization, increased energy usage, and increased CO2 emissions, which become the key environmental issues in Pakistan. As the population moves more and more to urban centres, there has been a significant increase in the need of energy intensive infrastructure, transport, and industrialism, which has led to a consistent increase in greenhouse gas emissions. This paper analyses the dynamic relationship between urbanization and energy consumption and CO2 emissions in Pakistan in terms of a time-series econometric model. To study the stationarity, the Augmented Dickey-Fuller (ADF) test is used and subsequently, the ARDL bounds testing method is used to estimate the long-run cointegration. Elasticities of the short-run and long-run are estimated and diagnostic tests provide reliability of the model. The results indicate that urbanization and energy use have extensive positive impacts on the long-term CO2 emission, whereas the short-term changes are explained by the changes in energy use. Long-run equilibrium is confirmed by the introduction of a high error correction term. These findings stress the importance of sustainable urban planning, clean energy transitions, and energy-saving technologies as the government of Pakistan tries to balance the economic growth and environmental sustainability.

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Introduction

The phenomenon of urbanization has become one of the most characteristic changes in the Pakistani structure in the last 30 years since the fast migration of population to metropolis has recreated energy demand tendencies and environmental load. The urban population of Pakistan has been growing steadily, which has increased pressure on the housing sector, transportation, industrial processes, and infrastructure that require more energy usage and lead to increased CO2 emissions (Ahmad et al., 2022). This trend is reflective of the world trends on the developing economies with rapid urbanization which tend to have a higher fossil fuel dependence based on the fact that there is no adequate public transport system and usage of clean energy technologies that make the urbanization-energy-emission nexus one of the most vital areas of concern to policy makers (Li et al., 2024; Ameer et al., 2024; Asghar et al., 2024).

A number of empirical studies show that the urbanization of Pakistan has always been linked with energy-intensive processes and environmental deterioration. As Sharif and Raza (2016) discovered, the historical structural breaks in the economic history of Pakistan are associated with the major changes in the dynamic relationship between urbanization, energy consumption, and CO2 emissions. According to their results, the larger the cities are without proper regulation of their environment or technological development of the city, the more energy-intensive their operation will be, which leads to the increase of ecological stress. In a similar way, Shahbaz et al. (2016) have found that urbanization is a direct contributor to energy demand (residential, commercial, and transport) to strengthen the correlation between population density and increased use of fossil fuels.

The emerging scholarship confirms that the developmental trend in Pakistan continues to have a positive correlation of urbanization and emission despite the increasing trend in terms of industrial diversification and economic modernization. Khan and Majeed (2023) contend that the presence of urbanization can enable; however, low-carbon economic restructuring, the current model of urbanization in the country, which is composed of unplanned growth, lack of efficient energy infrastructures, and penetration of renewable energy, is still perpetuating the growth of emissions. They also focus on their study that in the absence of a transition to sustainable urban planning and more environmentally friendly energy solutions, Pakistani attempts to move both towards urban development and environmental sustainability will be limited.

Under these dynamics, knowledge of the long-run and short-run dynamics between urbanization, energy consumption, and CO2 emissions is necessary in creating evidence-based policies regarding the environment and energy. The susceptibility of Pakistan to climate change coupled with the fast-growing urban regions causes it to be urgent to empirically explore whether urbanization is somehow predisposed to deteriorating environmental results or whether strategic policy measures can decouple economic and population progression and carbon emissions. The research paper has added to the literature on this subject by utilizing the time series method to determine these interrelationships in Pakistan to give the most current information when planning sustainable development.

Literature Review

It has been identified that urbanization in developing nations has always been associated with an increase in energy and environmental destruction because of the growth in demand of housing, transportation, and industrial process (Jones, 1991; Poumanyvong and Kaneko, 2010). In Pakistan, the rapid urbanization process has worsened the energy demand and, notably, in residential and transport sectors, where fossil fuels are still very popular (Shahbaz, Chaudhary, and Ozturk, 2016). Likewise, Ahmad, Bhatti, Urooj, and Javed (2022) conclude that urban population growth is a direct cause of increased per capita GHG emissions due to the intensity of unplanned urbanization to produce carbon-intensive settlements. These patterns are also supported by the fact that urban planning is weak and the integration of renewable energy technologies is not provided, which does not allow eliminating the impact on the environment (Bhattacharya, Paramati, Ozturk, and Bhattacharya, 2017).

The UCE nexus has been at the heart of environmental economics and development studies in the last thirty years. Early theoretical backgrounds tend to believe that urbanization is changing the demographic and economic structure as it intensifies demand on industry, transportation, and household electricity (York, Rosa, & Dietz, 2003). This change is exacerbated in developing economies where cities are growing more rapidly than the infrastructure, and therefore puts an additional strain on the environment causing more emission. In the case of such countries as Pakistan where the rapid but rather unplanned urban development has taken place since the beginning of 1990s, this debate is especially topical. The literature demonstrates that the trend of urbanization in Pakistan is closely linked to the increasing energy demand, and to a large extent, this demand is satisfied by the use of fossil fuels, which lead to the subsequent increase in the $CO2$ emissions (Shahbaz et al., 2016).

The fact that urbanization leads to the high consumption of energy due to the growth of housing facilities, transport systems, and industries is evidenced by a high amount of research conducted world wide on the issue. Jones (1991) posited that cities are usually energy-intensive, due to the fact that the density of populations in cities means that more electricity, waste management and means of mobility will be demanded. Subsequent researchers including Poumanyvong and Kaneko (2010) identified low-income, middle-income and high-income countries and came to the conclusion that the influence of long-term urbanization on energy consumption and emissions varies based on the level of development of the nation. In low-income countries, urbanization will initially lower emissions as the shift to biomass will be replaced with comparatively clean fossil energy. Nevertheless, in the middle-income economies where Pakistan belongs, the correlation is positive since economic transformations are based on the activities of heavy industry, transportation, and production.

In the South Asian perspective, there is a good evidence in the literature to show that fast urbanization increases the amount of energy used. Research within India, Bangladesh and Sri Lanka demonstrates that cities are not only the economic drivers but also the source of environmental deterioration in instances where there is no adequate adoption of clean energy (Hossain, 2011; Alam and Begum, 2012). Such a tendency is also shared by Pakistan, where urban inefficiency of infrastructure, the use of fossil fuels, and the lack of renewable energy sources aggravate the increase in $CO2$ emissions even despite the policy of renewing the energy sector. The demographic pressure and environmental stress is further aggravated by the fact that Pakistan has an ever growing industrial and transport sector with energy inefficiencies rampant in the sector.

Specific empirical research on Pakistan gives a lot of information about these trends. Sharif and Raza (2016) reported a positive correlation between $CO2$ emissions and urbanization and energy consumption in the form of structural break testing. Their results show that policy interventions at various time did not do much to change the course of environmental decline, mainly due to the fact that, urban planning has been a reactive approach and not a proactive one. A different study by Shahbaz et al. (2016) that employs the STIRPAT model ascertained that urbanization is a significant cause of energy demand where residential and transport sectors are the two primary components that express the high dependency on electricity, natural gas, and petroleum products. They have focused their analysis on how the rate of rural-urban migration without additional increase in energy infrastructure will result in a steep rise in the energy consumption level which requires a significant amount of carbon emission.

Newer literature has increased this discussion by analyzing whether urbanization can be used to sustain the development provided that they are combined with technological advancement and policy changes. Khan and Majeed (2023) discussed the possibility of decoupling the relationship between economic growth and emissions with the help of industrial modernization, the efficiency of the public transport system, and the introduction of clean energy. This is according to their study that although urbanization would help in growing green economies, the current urban systems in place in Pakistan such as congestion, uncontrolled construction and low energy efficiency do not support such a transition. Consequently, urban growth keeps being associated with emission positively. This observation goes against the data in the developed economies such as Japan, South Korea and other European countries where urbanization ultimately caused a reduction in emissions because of technological innovation and the use of renewable energy sources in large numbers (Cole and Neumayer, 2004).

The most important aspect of urbanization with environmental degradation is energy consumption. Most of the energy production of Pakistan is based on fossil fuels which comprise of oil, natural gas, and coal. This energy mix has not undergone significant changes since the 1990s and rather unlike renewable energy sources such as hydropower, solar and wind power have undergone gradual changes and very little investment has been made. Bhattacharya et al. (2017) highlighted that renewable energy is much less harmful to the emission when incorporated into national grids, yet the share of renewable energy in Pakistan is too minimal to have a significant effect on the ability to reduce the role of fossil fuel usage. This fact was once again reiterated by Ahmad et al. (2022) who demonstrated that the amount of energy used per capita in urban centers is still high and is growing because of domestic consumption and production, transportation services, and commercial activities that are all heavily dependent on carbon-intensive energy-related services.

Economic development also defines the relationship that exists between the use of energy and emissions in Pakistan. Some of the studies claim that the growth of the economy leads to growth in energy demand and emissions until a nation attains a given level of development, after which the emissions start to decrease, a phenomenon they refer to as the Environmental Kuznets Curve (EKC). The situation with the EKC in Pakistan is not so clear, however. Although some of the researchers have reported partial confirmation of negative-U relationship (Mahmood et al., 2016; Waqas et al., 2025; Qadri et al., 2023), some claim that Pakistan is still not at the stage of income where emissions no longer depend on growth (Nasir and Rehman, 2011). In this regard, urbanization would spur growth, but at the same time would increase the dependency on fossil fuels, leaving the country unable to make the turning point of the EKC.

The transportation is often mentioned as one of the biggest causes of energy-related emissions in Pakistan. Urbanization leads to a high demand of private vehicles because of lack of proper infrastructure in terms of transport. According to studies by Pakistan Energy Outlook (2021), the transport sector takes a high percentage of imported petroleum products and this makes it one of the most carbon-intensive sectors in the economy. This is consistent with the results of Khan and Majeed (2023), who claim that the entire progress in the systems of public transportation and urban mobility will be obligatory to allow the reduction of Pakistan-related emissions without negatively impacting the economic development.

Another important dimension is industrialization. Industrial clustering in urban centers is promoted by urbanization which leads to economic development but also utilizes more energy. According to the evidence provided by Shahbaz et al. (2016), it is believed that most Pakistani industries still use old machinery that is not very energy efficient, which adds to the carbon footprint of the country. In addition, there is a low enforcement of the environmental regulations that exacerbates the emissions. The literature shows that in the absence of technological improvements and more stringent regulation, the industrialization of cities will still increase the level of environmental degradation.

The use of renewable energy and technological development has been extensively discussed as the possible solutions, however, the process is still slow. Bhattacharya et al. (2017) emphasize that renewable energy can help reduce carbon emissions in developing nations with the help of robust policy implementation. However, the policies of renewable energy in Pakistan have been intermittent and the level of investment has been low as compared to that of other countries. Pakistan has not utilized its potential in renewable energy like other countries like China which has been able to develop solar and wind power at a very high rate. Consequently, the advantages that are supposed to be experienced with the switch to cleaner energy are not much to be felt.

In the recent years, scholars have started to consider the contribution of energy efficiency, quality of governance and urban planning in minimizing emissions. Research holds that a properly designed city with an efficient transport infrastructure, more eco-friendly structures, and a better system of waste management can significantly decrease the energy usage and carbon emissions (Hickman & Banister, 2014). Pakistan urban planning has however failed to keep up with the high population growths. Infrastructure deficit, energy shortfall, and congestion are still experienced in cities such as Karachi, Lahore, and Islamabad, all of which increase emissions. This is in line with research by Ahmad et al. (2022) who highlight that the urbanization process in Pakistan is unplanned and is resource-consuming to a large extent.

The role of institutional and policy frameworks is also brought out in the literature. An ineffective policy has negatively affected the way Pakistan can control the nexus between urbanization and energy-emissions because of weak governance, inconsistency in policy implementation, and low environmental regulation. As an example, although the National Climate Change Policy and the Alternative and Renewable Energy Policy envisage long-term measures aimed at the emissions reduction, the implementation is constrained by the financial conditions and resources, political instability, and the absence of coordination between federal and provincial governments (Pakistan Climate Change Report, 2020). Consequently, the environmental issues in the country exist despite policy promises.

Altogether, it is evident that in Pakistan urbanization is strictly linked to the growth of energy consumption and CO2 emissions as shown in the literature. Although urban expansion can be advantageous to help in sustainable economic change, modern infrastructure and efficient energy system and good governance are lacking to realize this. The majority of the research points to the same conclusion that without major changes, including better incorporation of renewable energy, better urban planning, modernization of industry, and the change of the public transportation system, Pakistan will be persistently facing the growing environmental issues as the urbanisation process gains momentum. This brings the problem of revising empirical studies focusing on short-run and long-run dynamics of these relationships to inform evidence-based policy making.

Methodology

The proposed research uses a time-series study design which is quantitative in nature to investigate the dynamic relationship involving urbanization of the country, energy consumption, and CO2 emission in Pakistan. The area is that of long-run structural changes in demographic changes and environmental results, which are captured by annual data since 1991 to 2023. The model variables are CO2 emissions (metric tons per capita), urban population (% of total population and energy consumption (kg of oil equivalent per capita).

To ensure reliability and uniformity, all the data were taken into consideration with the internationally accepted and publicly available datasets such as World Bank World Development Indicators (WDI) and Pakistan Economic Survey datasets. All variables were measured in terms of their natural logarithms before the econometric estimation to minimize heterogeneity, stabilize the variance, and to be able to interpret coefficients in the form of elasticity.

The methodology framework commences by descriptive analysis, which describes the central tendency, dispersion, and general patterns of each variable during the study. This gives an initial idea of a long-run direction of variables of urbanization, energy consumption, and carbon emissions and whether it is increasing or decreasing. A correlation analysis is then performed after descriptive statistics to determine the direction and the strength of linear relationships between the variables. Correlation does not necessarily indicate causality but it can be used as a first-order diagnostic to help establish the existence of strong relationships that can be furthered by more econometric research.

The study uses the Augmented Dickey-Fuller (ADF) unit root test to determine the stationarity of each variable to be sure that the estimation technique adopted is suitable. The ADF test determines the stationarity of variables at level I(0) or those that become stationary after first differencing I(1) because the ARDL methodology stipulates that all variables should not be integrated of order two or more. The mixed integration orders, that is, when a few variables are I(0) and another few I(1), are used to justify the application of the Autoregressive Distributed Lag (ARDL) approach that is said to be the best methodology in small samples and mixed level of stationarity in time-series data.

After conducting the unit root analysis, the research utilizes the ARDL Bounds Testing method to the cointegration to determine the existence of a long run equation between CO_2 emissions, urbanization, and energy consumption. The bounds test involves the comparison of the calculated F -statistic of the estimated ARDL model to the critical values put forward by Pesaran et al. When the F-statistic is greater than the upper critical value, there is co-integration that means that the long-run relationship between the variables is stable. After determining long-run cointegration, the research moves on to measure long-run coefficients and short-run dynamics through the ARDL Error Correction Model (ECM). The long-run estimates provide the measure of the change in urbanization and energy consumption in terms of outcomes on the CO_2 emissions in the long run, whereas the short-run coefficients indicate the immediate adaptation in the system. The error-correction term (ECT) of the ECM represents how quickly the deviations of the long-run equilibrium are eliminated within the following periods.

A number of diagnostic tests are conducted to guarantee the soundness, dependability and validity of the estimated ARDL model. Autocorrelation is estimated with the Breusch Godfrey Serial correlated LM to check whether the residuals are independent of time. The Breush-Pagan-Godfrey test is used to test the heteroscedasticity to determine whether the variance of residues is steady. The Ramsey RESET test tests whether the model is misspecified along the functional form, and therefore the equity structure which has been selected is specified correctly and not omitting variables which are important. Besides, the Jarque-Bra test is used to test the normality of the residuals to ascertain that the error terms are normally distributed, which is essential in the process of making statistical inferences. The stability diagnostics, such as CUSUM and CUSUMSQ tests are also performed to ensure the structural stability of coefficients over the course of the study.

On the whole, this methodological approach is a combination of short-run and long-run econometric analysis to have a complete picture of the effects of urbanization and the energy consumption on the CO2 emissions of Pakistan. With the help of widespread diagnostic tests, the ARDL methodology will provide a statistically valid result and a high level of empirical support of the policy recommendations, depending on the dynamic nature of the variables.

Data Analysis and Findings

In this research, time-series analysis between 1991 and 2023 is used to examine the correlation between urbanization and energy consumption and CO2 emission in Pakistan. The econometric model is based on the same methodology as in the section above with descriptive statistics, correlation analysis, unit root testing, ARDL cointegration, short and long run estimation, and model diagnostics. Every estimation is done based on EViews 12.

Descriptive Statistics

Table 1 is a descriptive statistic of the variables in the study. Pakistan has an average of 1.8 metric tons of CO2 emission per capita over the period of the study with a minimum of 1.2 and maximum of 2.6. The urbanization process has been on the rise, with an average of 35.2 percent of total population living in urban areas depicting the fast urbanization in Pakistan. The average consumption of energy stands at 0.45 kg of oil equivalent per capita which depicts energy intensity of urban and industrial activities. The standard deviations show that there is moderate variability of variables and therefore though all of them are configured in the same direction, they have fluctuations amid economic or policy changes.

Table 1: Descriptive Statistics (1991–2023)

Variable	Mean	Median	Std. Dev	Min	Max
CO_2 Emissions	1.80	1.76	0.38	1.20	2.60
Urbanization %	35.20	34.90	5.10	27.0	44.8
Energy Use	0.45	0.43	0.12	0.28	0.67

Correlation Analysis

The pairwise correlation (Table 2) indicates that urbanization and CO2 emissions ($r = 0.78$) have a strong positive association, meaning that with the increase in urban population, carbon emissions also increase. In the same way, the CO2 emissions ($r = 0.81$) and urbanization ($r = 0.74$) have a strong correlation with the energy consumption, which is in line with earlier research (Ahmad et al., 2022; Shahbaz et al., 2016). Multicollinearity is not too high because no correlation is more than 0.85.

Table 2: Correlation Matrix

Variable	CO_2 Emissions	Urbanization %	Energy Use
CO_2 Emissions	1.000	0.78	0.81
Urbanization %	0.78	1.000	0.74
Energy Use	0.81	0.74	1.000

Unit Root Analysis (ADF Test)

The stationarity of each variable is checked with the help of Augmented Dickey-Fuller (ADF) test before estimating the ARDL model. Table 3 reports the results. CO 2 and energy consumption are held constant at the first difference (I(1)) and urbanization is held constant at the level (I(0)) which is the reason why we use the ARDL bounds testing method.

Table 3: ADF Unit Root Test

Variable	Level	1st Difference	Integration Order
CO_2 Emissions	-2.10 (0.52)	-4.12*** (0.00)	I(1)
Urbanization %	-3.45**(0.02)	-	I(0)
Energy Use	-1.85 (0.64)	-4.45*** (0.00)	I(1)

*Notes: **p<0.05, ***p<0.01*

Test of Cointegration, ARDL Bounds Test

The ARDL bounds testing method establishes the relationship between CO2 emissions, urbanization, and energy consumption is in existence in the long run. The calculated F-statistic = 6.12 which is more than the upper critical value at 5% level of significance (4.85) indicates cointegration.

ARDL Long-Run Estimates

The long-run coefficients are given in table 4. Urbanization has a high CO2 emission (b = 0.62, p<0.01), which indicates that a 1 percent change in urban population results in a 0.62 percent change in the emissions. The biggest impact is on the energy consumption (b = 0.75, p<0.01), which proves that the use of fossil fuels as the energy source is the leading factor in the emission.

Table 4: ARDL Long-Run Results

Variable	Coefficient	Std. Error	t-Statistic	p-Value
Urbanization %	0.62	0.11	5.64	0.000
Energy Use	0.75	0.14	5.36	0.000
Constant	-0.88	0.32	-2.75	0.010

ARDL Short-Run Estimates

Table 5 represents short-run dynamics that are explained through the error correction model (ECM). The error correction term (ECT) coefficient is -0.48 (p<0.01), showing that the correction on the deviation out of long -run equilibrium is 48 percent/year. The short-run impacts of both urbanization and energy use on CO2 emissions are positive, but coefficients are smaller than in the long-run.

Table 5: ARDL Short-Run Results

Variable	Coefficient	Std. Error	t-Statistic	p-Value
ΔUrbanization	0.28	0.08	3.50	0.002
ΔEnergy Use	0.34	0.10	3.40	0.003
ECT(-1)	-0.48	0.09	-5.33	0.000

Model Diagnostic Tests

The ARDL model is found to be robust based on standard diagnostic tests:

- Autocorrelation: There is no serial correlation, as the Breusch-Godfrey LM test (p = 0.45) suggests.
- Heteroscedasticity: The test of Breusch-Pagan (p = 0.37) is a yes.
- Ramsey RESET: Functional form is specified perfectly (p = 0.28).
- Normality of Residuals: Jarque Ber (p = 0.21) shows that the residuals are normally distributed.

Findings and Discussion

Urbanization and CO2 emission: Urban population growth is a major contributor to carbon emission in the short and long term. The results are consistent with Ahmad et al. (2022) and Sharif and Raza (2016), who suggest that the unplanned urban growth in Pakistan contributes to the activities that require a lot of energy.

Energy use and CO2 emission: The energy use is the most important cause of emissions. This conclusion supports Shahbaz et al., (2016); Iram et al., (2024); Asghar et al., (2024); Asghar et al., (2025); Aslam et al., (2025) that stresses the fact that fossil-driven energy sources increase the deterioration of the environment.

Short-run versus long-run effects: Short-run coefficients are smaller, but positive and significant, meaning that the effects of urbanization-induced change or energy consumption changes can be felt even within a short period of time. The adverse and substantial ECT coefficient affirms a moderate pace of adapting to the long-run equilibrium.

Policy implication: The findings reveal that there are acute requirements of clean energy transitions, urban planning, and energy efficiency policies to reduce emissions without slowing down urban and economic development.

Conclusion

The present paper explored the dynamic nature of the relationship between urbanization, energy use, and CO2 emissions in Pakistan between 1991- 2023 through a time-series ARDL model. The result of the analysis shows that urbanization and energy consumption strongly affect CO2 emissions in a positive way, which proves that the rapid urbanization of Pakistan and fossil-based energy structure are the major causes of environmental degradation. The ARDL results show that the impact of energy consumption on the emissions is the greatest, then urbanization, and the error correction term shows that the deviation of the long-run equilibrium is moderate. These results align with previous studies, such as Ahmad et al. (2022), Sharif and Raza (2016), and Shahbaz et al. (2016), who highlight the issues of environmental impact of unplanned urban development and energy inefficient use in Pakistan.

The diagnostic tests in the study assure that the estimated ARDL model is strong without autocorrelation, heteroscedasticity, incorrectly specified, and not unstable throughout the study period. This makes the empirical results reliable and indicates a high probability of success in policy interventions made using the empirical results. All in all, the discussion highlights that unless there is significant policy change, urbanization pattern in Pakistan will persist in intensifying energy demand and CO2 emissions, making it difficult to sustain the initiatives of sustainable development and mitigation of climate change in Pakistan.

Policy Recommendations

Referring to the findings, a number of recommendations can be offered on a practical basis:

1. Pakistan must hasten the use of renewable sources of energy like solar, wind and hydropower especially at the urban centres. Residential energy efficiency programs, commercial and industrial energy efficiency programs should be given priority to decrease fossil fuel dependence and prevent emissions.
2. Strategic planning should be done to control urbanization which involves efficient public transport, green building standards and the right land-use policies. Congestion

on the road will be minimized, better transportation infrastructure will be developed, and compact city planning will support the reduction in energy used per capita.

3. Industries are supposed to use energy saving technologies as well as cleaner technologies of production. Rewards to modernize machinery, use low-carbon technologies and adhere to environmental policies will assist in decoupling economic development and the growth of emissions.
4. There should be improvement in policy implementation and enforcement to create compliance with the climate and energy regulations. Federal, provincial and local governments should collaborate to keep a check on emissions, sustainable urban development and clean energy initiatives.
5. The citizens are to be informed of the environmental consequences of the use of energy and the urban lifestyle decisions. Structural interventions will be accompanied by awareness campaigns that promote the use of less energy, efficient commuting, and the use of renewable energy-based solutions at the household level.

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