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State Policy Responses to Urban Development and CO_2 Emissions in Kazakhstan: The Role of Global Uncertainty in Shaping Environmental Governance

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ABSTRACT

This paper examines the dynamic link between urbanisation and carbon dioxide (CO_2) emissions in Kazakhstan with the focus on the impact of global uncertainty. Using annual data from 1990 to 2020, the study uses an autoregressive distributed lag (ARDL) model in error correction form, based on the Environmental Kuznets Curve (EKC) hypothesis. The findings of the paper show that GDP per capita is the main factor influencing both short- and long-term CO_2 emissions. Urbanisation dramatically lowers emissions over time, defying popular belief and indicating efficiency improvements in Kazakhstan's cities. Crucially, the insignificance of the WUI and its interaction term indicates that global uncertainty neither directly affects emissions nor modifies the urbanization - emissions link, contradicting the findings of other authors. These findings have significant policy ramifications: Kazakhstan needs to increase the use of renewable energy sources, diversify its energy sources, and design its cities wisely to divorce growth from emissions. When properly controlled, urbanisation can be a tool for sustainable growth. The analysis concludes that global uncertainty has no discernible impact on Kazakhstan's emissions trajectory and that domestic structural reforms have a greater impact on emissions reduction than external shocks.

Keywords: Urbanization, CO_2 Emissions, World Uncertainty Index, Renewable Energy, Ecological Footprint
JEL Classifications: Q53, Q58, R11

1. INTRODUCTION

Mitigating climate change is an environmental imperative and a major issue of public policy and administration in all the countries. However, most countries that suffer from it are not studied enough, for example resource-dependent economies like Kazakhstan (Poberezhskaya and Bychkova, 2022). One of the most carbon-intensive countries in Central Asia, Kazakhstan, with over 12 metric tons of CO_2 emissions per capita during the 1990s-2010s, is faced with dual challenges: sustaining economic growth and achieving environmental sustainability (Hasanov et al., 2019). The challenges are more prominent in the urban context in which city planning, energy infrastructures, and population density are involved in the making of the country's environmental profile.

Urbanization is part of Kazakhstan's national development planning and, by extension, its systems for energy consumption, transport, and housing (Tleppayev et al., 2023). Aligned with international climate goals, the Kazakh government is preparing to undergo great policy change. Some of the key policy documents include the Concept for Transition to a Green Economy (2013), the Doctrine for Achieving Carbon Neutrality by 2060, the National Climate Change Adaptation Plan, and the Renewable Energy Development Strategy. These policy documents emphasize the administrative commitment to decarbonization, and sustainable urban development made by the government.

Nonetheless, serious gaps in implementation exist pertaining to aligning urban development with climate goals, especially under conditions of global economic and policy uncertainty (De Ruschi et al., 2024). Public administrators face uncertainty not only from domestic variables (e.g., budget constraints, institutional capacity) but also from volatile external environments, which may, for example, alter investment in renewable energy, delay infrastructure upgrades, or shift their focus from long-term sustainability (Atkinson, 2019; Ivanovski and Marinucci, 2021). The present paper seeks to shed light on the discussion of whether global uncertainty moderates the relationship between urbanization and CO_2 emissions in Kazakhstan, thus providing insights for national level planning and climate governance.

This research estimates ARDL error correction models using annual data from the early 1990s to 2020, with the help of bounds testing, a Bai - Perron structural break test (2006), and unit root tests. Results indicate that whereas urbanisation dramatically lowers long-term emissions, GDP development increases emissions both in the short and long term. Global uncertainty has no discernible impact on renewable energy. The results highlight the significance of Kazakhstan's active decarbonisation measures and sustainable urban development.

2. EMPIRICAL REVIEW

The 21st century was the fight against grave environmental issues amid high-paced urbanization, economic growth, and reformed patterns of energy use (McGee and Mori, 2021). Cities due to greater demand for energy, land-use change, and infrastructure development, generate a lot of carbon emissions. Simultaneously, technological advances and the integration of the world economy create new opportunities for improving efficiency and reducing emissions, but with disparate levels of adoption across countries (Sarkodie et al., 2020). For an emerging economy such as Kazakhstan, therefore, the interaction between development and environmental degradation is particularly important, given its structural dependence on extractive industries and fossil fuels (Colapinto, 2020).

In this narrative comes the design to look at the nexus between economic development and environmental quality in terms of the Environmental Kuznets Curve hypothesis (EKC). The claim of this hypothesis is that environmental degradation increases with initial income growth but then begins to decline after income attains a certain level-thirdly through shifts in structural composition, technological advancement, and institution strengthening (Grossman and Krueger, 1995). The evidence for and against the EKC in Kazakhstan is mixed. Akbota and Baek (2018) find evidence of an inverted-U shape relationship between GDP per capita and carbon emissions, implying that the country may be currently on the threshold of change. Yet Hasanov et al. (2019), among others, find a steady increase in emissions with economic growth-an indication that economic growth in Kazakhstan is still largely carbon-intensive and that decoupling processes are yet to be developed.

Urbanization is really a variable in the equation because it affects emissions in many ways, with sometimes opposing effects (Wei and Lahiri, 2022). While higher urbanization is typically associated with a rise in energy consumption due to denser populations, increased transportation, and industrial clustering (Jones, 2016), there exist urban efficiency outcomes that result from economies of scale, better infrastructure, and policy-induced innovations in energy use. Thus, the direction and magnitude of urbanization on emissions depend on how urban growth is managed (Sheng et al., 2017). For Kazakhstan, Raihan and Tuspekova (2022) find a long-run positive relationship between urbanization and CO_2 emissions, suggesting that thus far, urban growth has not been in line with environmental efficiency. However, energy policies, technological advances, and institutional quality may provide some form of paths for deviation from this trend.

Theoretically, upon the implementation of renewable energy policies, the conflict between urban growth, economic development, and environmental sustainability should be settled (Zhang et al., 2024). Empirically, however, studies uphold the inverse relationship between renewable energy share in total energy consumption and carbon emissions (Bhattacharya et al., 2017; Destek and Aslan, 2017), while Kazakhstan has lapsed, increasingly distanced from these best practices. Despite having an official Renewable Energy Development Strategy and other sustainable development-related commitments, in practice, renewable sources accounted for a very small share of Kazakhstan's national energy mix for many years (Smagulova et al., 2024). Thus, until now, they hardly could make a noticeable effect on cutting emissions in Kazakhstan, either in absolute or statistical terms inside empirical models (Zhumadilova et al., 2023).

Global uncertainty on the economy and on policy formation has become a potential yet neglected factor that causally affects environmental outcomes (López et al., 2022). The World Uncertainty Index (WUI), explained by Ahir et al. (2018), captures the spontaneous outlooks in the markets affecting investments, trade, and policy execution (Federal Reserve Bank of St. Louis, 2024). There are increased views that uncertainty can limit emissions because it is slowing economic and industrial activities (Baker et al., 2016); uncertainty can also limit investments in clean technology, causing a buildup or delay of reforms (Ayad et al., 2023; Fu et al., 2022). For instance, Fasanya and Arek-Bawa (2025) show that in South Africa, there is the role of interactions between urbanization and global uncertainty in substantially altering the emissions trajectory, which represent a hitherto overlooked moderating effect. Whether Kazakhstan holds a similar dynamic is a question for further empirical study.

Kazakhstan offers an excellent case study because it is a resource-dependent, transition economy, which thus gives sustainability ambitions an impetus (Rakhymzhan et al., 2024). Multiple national strategic documents implemented by the government, including the Concept of Transition to a Green Economy and Doctrine for Achieving Carbon Neutrality by 2060, provide a formal framework for the implementation of decarbonization and urban sustainability (Platonova-Oquab and Shenvi, 2023). However, the extent to which these strategic documents have been reflected in actual emissions outcomes, all under global volatility, is to be explored empirically. The observable disconnects or misalignment between policy intent and implementation is urgently at the forefront of public administration and environmental policy implementation.

Although there is an abundance of literature on the country-specific effects of economic growth and urbanization on the environment in Kazakhstan, substantial research gaps remain on how global uncertainty interacts with domestic emissions drivers. Prior studies have largely neglected to examine the modifying effect of uncertainty on the urbanization - emissions nexus and some of the few that have done so have not incorporated uncertainty measures directly into econometric modeling. Furthermore, the degree of success enjoyed by renewable energy policies operating within this complex will also need an appraisal. The present study seeks to fill these gaps by adopting the STIRPAT approach and EKC hypothesis frameworks to investigate the direct effects of urbanization, GDP, and renewable energy on emissions and the moderating role of global uncertainty on Kazakhstan's emission path over time.

3. MATERIALS AND METHODS

The object of the study is the Republic of Kazakhstan, the largest state in Central Asia and ranked ninth in the world by area. It is located at a strategic crossroads of Eurasia and has demonstrated high rates of economic growth in recent decades. Kazakhstan's economy is characterized by a high share of energy in its GDP structure and increasing dependence on global economic processes. Economic activity is concentrated mainly on energy, mining, agriculture, and services, with urbanization accompanied by the development of infrastructure, construction, and industrial production in large cities such as Almaty, Astana, Shymkent, and Aktau.

Kazakhstan implements strategic documents aimed at sustainable development and decarbonization, such as the Concept of Transition to a "green economy" (2013), the Doctrine of Achieving Carbon Neutrality by 2060, the National Climate Change Adaptation Plan, and the Renewable Energy Development Strategy. These programs form the institutional framework for achieving goals related to reducing carbon emissions, stimulating development of renewable energy sources, regulating urbanization rates, and ensuring sustainability of urban infrastructure. Therefore, Kazakhstan serves as an example of a territory for analyzing how government policies and public administration affect sustainable development processes in transitional economies.

For the empirical analysis, secondary data in time series format for the period 1990-2022 were used. The main sources were the annual official statistical data from the Bureau of National Statistics in the Republic of Kazakhstan and the official databases from the World Bank, International Monetary Fund and Global Ecological Footprint Network. Initial indicators were selected based on relevance to research objectives, availability of long-term observations and compliance with reproducibility requirements. All-time series were brought to a single measurement scale to ensure comparability. This ensured the validity and representativeness of the empirical basis used.

This study uses yearly statistical data for Kazakhstan for the period from 1990 to 2022. In addition, the ecological footprint biocapacity data (ln_EF) have been included for descriptive purposes to offer a broader environmental perspective. The primary data sources include the Bureau of National Statistics of Kazakhstan, World Bank, IMF, and the Global Footprint Network.

Table 1 is the summary of the study variables, codes, and full names of the variables, as well as their sources. The variables were selected based on their pertinence to the study objective: examining economic, social, and global factors that affect sustainable development and public policy formulation. Hence, the share of urban population and renewable energy consumption are used as indicators by which they evaluate state strategies in urban infrastructure planning and the transition to clean energy. Per capita CO_2 emissions are used as a prime indicator to gauge environmental policy implementations. Economic growth is measured using real GDP per capita according to the core set in the Environmental Kuznets Curve (EKC). Global economic uncertainty is finally entered as a possible moderator which can influence national regulatory capacity vis-à-vis international risks.

Figure 1 illustrates the sequential methodological stages employed in the empirical study, from data preparation to policy-oriented interpretation of results.

To stabilize the variance and also to interpret coefficients as elasticities, all variables were transformed into their natural logarithms. Due to the structural changes found in the Bai - Perron multiple breakpoint test, a dummy variable for the year 2006 (D_{2006}) was included in the model. Correlation and descriptive statistics based on Pearson's correlation coefficient were calculated to understand the basic relationships among the variables and to provide a first detection of multicollinearity, which was further investigated using analysis from the Variance Inflation Factor (VIF).

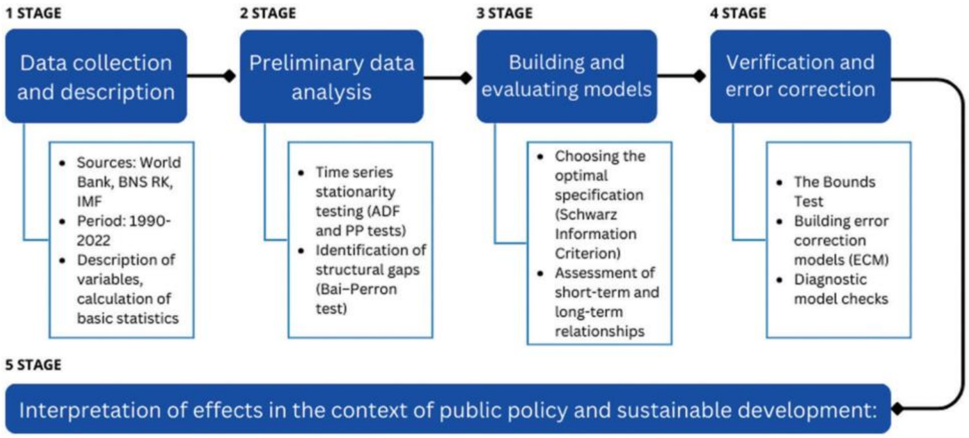
In finding the order of integration, unit root tests, namely the Augmented Dickey - Fuller (ADF) test and the Phillips - Perron (PP) test, were performed. The results stated that none of the series were integrated of order two, permitting the use of the method of ARDL bounds testing for testing cointegration. Two models have been specified; Model 1 does not include the interaction term, whereas Model 2 introduces an interaction between urbanization and global uncertainty (ln_URB × ln_WUI). The Schwarz Information Criterion (SIC) was used to find the appropriate lag structure for each model.

Table 1: Description of study variables

Code	Full Name	Source
CO2	Carbon dioxide (CO_2) emissions (metric tons per capita)	World Bank, Bureau of National Statistics
GDP	Gross Domestic Product per capita (constant 2015 US$)	World Bank, Bureau of National Statistics
RWN	Renewable energy consumption (% of primary energy)	World Bank
URB	Urban population (% of total population)	World Bank
WUI	World Uncertainty Index (annual, global)	Federal Reserve Bank
EF	Ecological footprint biocapacity (gha per person)	Global Footprint Network

Source: Authors

Figure 1: Methodological stages of empirical research and policy interpretation framework



Source: Authors

The ARDL method can be expressed in error correction form (ECM), allowing the examination of short-run dynamics and long-run equilibrium relationships. The coefficient of the error correction term (ECMt−1) shows how fast the system corrects any disequilibria occurring from the long-run relationship. Diagnostic statistics, such as R-squared, adjusted R-squared, and stability tests, were done to make sure that the models are robust and sound.

Two ARDL models are estimated: Model 1 (ln_ CO_2 as a function of ln_GDP, ln_RWN, ln_WUI, ln_URB, and D_{2006}) (1) and Model 2 (ln_URB×ln_WUI in place of ln_WUI) (2). The Schwarz Information Criterion (SIC), which favours a condensed ARDL (1,0,0,0,0) specification, is used to choose lag durations. After adjusting for the structural break, the trend term was not statistically significant, hence it is not included.

The general ARDL-ECM form estimated is:

Long-run equation:

$$ln(CO2_t) = \alpha_0 + \alpha_1 \times ln(GDP_t) + \alpha_2 \times ln(RWN_t) + \alpha_3 \times ln(URB_t) + \alpha_4 \times ln(WUI_t) + \alpha_5 \times D_{2006} + \varepsilon_t \quad (1)$$

In Model 2, instead of ln_WUI separately, there is an *interaction term* between urbanization and uncertainty:

$$ln(CO2_t) = \alpha_0 + \alpha_1 \times ln(GDP_t) + \alpha_2 \times ln(RWN_t) + \alpha_3 \times ln(URB_t) + \alpha_4 (ln(URB_t) \times ln(WUI_t)) + \alpha_5 \times D_{2006} + \varepsilon_t \quad (2)$$

Where:
$ln(CO2_t)$ - natural log of CO_2 (dependent variable)
$ln(GDP_t)$ - natural log of real GDP per capita,
$ln(RWN_t)$ - natural log of renewable energy consumption,
$ln(URB_t)$ - natural log of urban population share,
$ln(WUI_t)$ - natural log of the World Uncertainty Index,
D_{2006} - dummy variable capturing the structural break in 2006 (1 if year ≥ 2006, 0 otherwise),
α_0 - intercept term,
$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$ - long-run coefficients,
ε_t - stochastic error term.

The ECM (Error Correction Model) form shows short-term dynamics and the correction toward the long-run equilibrium:

$$\Delta\, ln(CO2_t) = \beta_0 + \sum\beta_i \Delta X_{t-i} + \varphi ECM_{t-1} + \upsilon_t \quad (3)$$

Where:
Δ - first difference operator,
β_i - short-run coefficients for lagged differences of explanatory variables,
ECM_{t-1} - lagged error correction term, measuring deviation from long-run equilibrium,
ϕ - speed of adjustment coefficient (expected to be negative),
ν_t - error term for short-run model.
ECM_{t-1} is the previous year's *deviation* from equilibrium. It is:

$$ECM_{t-1} = ln(CO2_{t-1}) - [\alpha_0 + \alpha_1 + ln(GDP_{t-1} + \alpha_2 \times ln(RWN_t) + \alpha_3 \times ln(URB_{t-1}) + \alpha_4 \times ln(WUI_{t-1}) + \alpha_5 \times D_{2006,t-1} \quad (4)$$

The central aspect of this analysis consists of lagged departure from long-term equilibrium, while the annual rate of adjustment is captured by the coefficient ϕ and is supposed to be negative, thus suggesting convergence to equilibrium. The long-run coefficients, α, and short-run dynamics, β, are simultaneously estimated using an Autoregressive Distributed Lag (ARDL) model that fits datasets with a mix of I(0) and I(1) variables. Additionally, dummy variable (D_{2006}) was added to allow for structural change in the period before or after 2006.

After estimations are made, cointegration tests are performed using the Bounds procedure put forward by Pesaran et al. (2001). Under this setup, cointegration exists when both the F-statistic and t-statistic on the ECM variable exceed the upper bound, and the reverse is true when both are below the lower bound. It is expected to be borderline due to the mixed integration of the variables; nevertheless, one would strongly argue for cointegration based on the argument of a significantly negative ECM coefficient in any case.

To verify robustness, tests for autocorrelation, normality of residuals, and homoskedasticity are performed. Further, R^2 and adjusted R^2 values are presented to assess model fit. This comprehensive approach, wherein ARDL estimation is combined with the structural break adjustment procedure and cointegration testing, facilitates the thorough examination of an array of partners to carbon emissions in the relatively policy-ridden space for sustainable development.

4. RESULTS AND DISCUSSION

This section presents the empirical results stemming from the time-series data for Kazakhstan from 1990 to 2020. The study begins with descriptive statistics and correlation tests as these would unveil the relationships among the key variables like GDP per capita, urbanization, share of renewable energy, and CO_2 emissions. Diagnostic tests, including unit root testing and structural break identification, are carried out accordingly to satisfy model diagnostics. This is followed by the estimation using the ARDL bounds testing and error correction modeling for both short and long-run effects of the selected variables, including global uncertainty as a moderating factor. The results of the multicollinearity test using the variance inflation factor (VIF) are presented in Table 2.

Table 2 shows that Model 1 has high multicollinearity between ln_GDP and ln_URB (VIF ≈ 10, correlation = 0.94), suggesting that income and urbanisation have developed in Kazakhstan nearly simultaneously. Because standard errors are overstated, it is challenging to separate their individual effects on CO_2 emissions. This is addressed in Model 2 by removing ln_WUI as a stand-alone variable and adding an interaction term (ln_URB × ln_WUI), which lowers all VIFs to about 1 and removes multicollinearity issues. The interaction term is a stable moderator because it has only a weak correlation with ln_GDP and ln_URB. According to these diagnostics, Model 2 offers a more trustworthy framework for evaluating the impact of global uncertainty. All of the variables' summary statistics are shown in Table 3 below.

Table 3 makes several points clear. First, the average ln_CO_2 in Kazakhstan is approximately 2.507, meaning that each person has about 12.3 metric tonnes of CO_2 (exp (2.507) ≈ 12.3). 7.7 tonnes (min exp (2.043)) to 16.2 tonnes (max exp (2.787)) are the range. This demonstrates that Kazakhstan is a high emitter per capita. A generally symmetric distribution of ln_CO across the time is suggested by the noteworthy median of 2.559 (≈12.93 tonnes), which is close to the mean. However, the standard deviation is not insignificant (0.203, i.e., around 20% fluctuation relative to mean).

In conclusion, the data show modest urbanisation and growing GDP, along with high and increasing CO_2 emissions, little use of renewable energy sources, and sporadic spikes in global uncertainty. Our regression analysis is framed by this.

Before executing the ARDL models it is important to see how these variables move together through correlation matrix. Pearson's correlation coefficients are displayed in Table 4 for the primary variables in Model 1 and Table 5 for the variables in Model 2 (where the interaction term is substituted for ln_WUI).

Table 4 shows that ln_ CO_2 has a substantial correlation with ln_GDP (0.891) and a modest connection with ln_URB (0.717). However, given their high intercorrelation (0.938), it seems likely that GDP is the driving force behind the urbanisation link. Given its limited importance, renewable energy (ln_RWN) has a weak negative association with emissions and almost no correlation with GDP or urbanisation. Only weak correlations are seen for global uncertainty (ln_WUI), indicating that it has no direct impact on growth or emissions.

The interaction term (ln_URB×ln_WUI) in Table 5 has weak correlations with every variable, indicating that there is no collinearity and that regression is required to capture any effect. Urbanisation and economic expansion are the primary drivers of emissions overall, whereas uncertainty and renewable energy have little direct impact and need more thorough modelling to determine their impact.

The test data for ADF and PP at levels and initial differences are shown in Table 6. These statistics (include a constant in the test equations and trend if appropriate in some circumstances) and show if the variables are stationary and which model should be used for further research.

Table 2: Variance inflation factors (VIF) for models 1 and 2

Model 1	VIF	Tolerance	Model 2	VIF	Tolerance
ln_GDP	9.816947	0.101865	ln_GDP	1.036715	0.964585
ln_RWN	1.114390	0.897352	ln_RWN	1.014447	0.985758
ln_URB	10.254410	0.097519	ln_URB × ln_WUI	1.040065	0.961478
ln_WUI	1.163024	0.859827			
Mean VIF	5.587193	0.178981	Mean VIF	1.030409	0.970488

Source: Authors

Table 3: Descriptive statistics

Variable	Obs	Mean	Standard deviation	Min	Median	Max
ln_CO2	31	2.506773	0.202773	2.043361	2.558994	2.786523
ln_GDP	31	8.825794	0.421195	8.160094	8.991796	9.310941
ln_RWN	31	0.545827	0.239632	0.095310	0.587787	1.029619
ln_URB	31	4.037421	0.011075	4.023564	4.036168	4.060271
ln_WUI	31	−2.407280	1.582056	−9.210340	−2.307420	−0.637770
ln_EF	31	1.488393	0.305935	0.602318	1.457264	2.255383

Source: Authors

Table 6 confirms that ln_ CO_2 and ln_GDP are I(1) by showing that they are non-stationary at level but become stationary after first differencing. Along with the interaction term and ln_URB, ln_RWN is stationary at level I(0). However, ln_URB exhibits inconsistent findings between ADF and PP tests, indicating trend-stationarity. Although ln_WUI is borderline, it is handled as I(1) for safety.

In conclusion, no series is integrated beyond I(1), and all variables are either I(0) or I(1), supporting the application of the ARDL bounds testing approach.

A visual examination in the mid-2000s indicated a potential structural break. A major structural break in 2006 was confirmed for both Model 1 and Model 2 when the residuals of a preliminary emissions model were subjected to the multiple breakpoint test developed by Bai and Perron (2003), which allows for up to two breakdowns. This conclusion is substantially supported by the F-statistics (Table 7).

A substantial structural change in 2006 was confirmed for both Model 1 and Model 2 by the Bai-Perron test, which strongly rejects the null hypothesis of no break (F-statistics: 45.3 and 149.5, much over the 1% critical value). This disruption most likely reflects Kazakhstan's economic regime change brought on by the country's rising oil exports and subsequent exposure to the global financial crisis of 2008. Model 2 indicates a potential second break (F = 14.946) for the 1 versus 2 break tests, while its reliability is reduced due to the small sample size. Therefore, to capture this significant structural shift and guarantee objective long-run estimates, a dummy variable D_{2006} (equal to 1 from 2006 onwards) was used.

This research, also, uses the Pesaran bounds test to determine whether there is a long-term equilibrium relationship between ln_CO_2 and the explanatory variables after estimating the ARDL models. The calculated t- and F-statistics for cointegration, as well as the test's critical value boundaries, are summarised in Table 8. Both Model 1 and Model 2 findings are shown.

Table 8 shows that neither model offers compelling evidence of cointegration: both Model 1's (1.749) and Model 2's (3.175) F-statistics fall below the 10% lower bounds. In a similar vein, the ECM t-statistics (−1.670 and −1.056) fall short of crucial values. Several factors, including the short sample size, sensitivity to the 2006 structural break, shifting correlations, or omitted variables, could account for this, even if it shows no cointegration at conventional levels.

However, paper proceeds using the error-correction term (ECM_{t-1}), as is typical in practice. Strong error-correcting behaviour and the presence of a long-run equilibrium are supported by the highly negative and significant ECM_{t-1} (around - 0.8) in both models. Therefore, economic theory and ECM importance support the interpretation of the long-run coefficients, even in the face of unsatisfactory limits test results.

The estimated ARDL-ECM results - Model 1 (no interaction term) is represented by Table 9, and Model 2 (with interaction) is represented by Table 10. Each table displays the short-term dynamics (β's for differenced terms, including the ECM term) and long-term coefficients (α's from the cointegrating equation).

Table 4: Pearson's correlation - Model 1 variables

Model 1	ln_CO_2	ln_GDP	ln_RWN	ln_WUI	ln_URB
ln_CO_2	1.000				
ln_GDP	0.891	1.000			
ln_RWN	−0.184	−0.066	1.000		
ln_WUI	0.110	0.173	0.086	1.000	
ln_URB	0.717	0.938	0.047	0.278	1.000

Source: Authors

Table 5: Pearson's correlation - Model 2 variables

Model 2	ln_CO_2	ln_GDP	ln_RWN	ln_URB	ln_URB×WUI
ln_CO_2	1.000				
ln_GDP	0.891	1.000			
ln_RWN	−0.184	−0.066	1.000		
ln_URB	0.717	0.938	0.047	1.000	
ln_URB×ln_WUI	0.108	0.170	0.087	0.275	1.000

Source: Authors

Table 6: Unit root tests (ADF and PP)

Variable	Augmented Dickey-Fuller			Phillips-Perron		
	Level t-stat	Diff t-stat	I(d)	Level t-stat	Diff t-stat	I(d)
LN_CO2	−2.491	−4.490***	I(1)	−2.490	−7.056***	I(1)
LN_GDP	−0.987	−4.054***	I(1)	−0.791	−4.297***	I(1)
LN_RWN	−3.587***	−3.825***	I(0)	−3.032**	−3.320**	I(0)
LN_WUI	−2.096	−8.546***	I(1)	−3.741***	−	I(0)
LN_URB	−4.097***	−3.820***	I(0)	2.858	−3.741***	I(1)
LN_URB×WUI	−3.409**	−5.480***	I(0)	−3.402**	−3.402**	I(0)
LN_EF	−1.207	−9.869***	I(1)	−1.316	−11.266***	I(1)

Significance at 1%, 5%. Critical values (approx) for ADF/PP at 5%: −2.96 (without trend), −3.57 (with trend). Tests include constant; trend included for ln_URB which is near a boundary case. Source: Authors

For years before 2006, dummy 2006+ = 1. The coefficient of the lagged error-correction term, ECMt-1, reflects the rate of adjustment. Both models produced an ARDL (1,0,0,0,0) form by using SIC for lag selection. Since both models explain the same variation in ln_CO_2, R2 and Adjusted R2 are the same for both models.

With a coefficient of roughly 0.688 ($P < 0.01$), short-run estimations demonstrate that changes in GDP per capita (Δln_GDP) have a large and positive impact on emissions, supporting the idea that economic activity directly leads to increasing CO_2 output. On the other hand, the interaction term (Δ(ln_URB × ln_WUI)), urbanisation (Δln_URB), global uncertainty (Δln_WUI), and the share of renewable energy (Δln_RWN) do not show statistically significant effects, indicating that short-term variations in these variables do not significantly affect emissions.

Table 7: Bai-Perron tests for structural breaks

Test date	Break test	F-statistic	1%	5%	10%
2006	0 versus 1	45.287	4.48	3.65	3.23
Model 1	1 versus 2	4.529	4.88	3.98	3.63
2006	0 versus 1	149.463	4.48	3.65	3.23
Model 2	1 versus 2	14.946	4.88	3.98	3.63

Source: Authors

Table 8: ARDL bound test for cointegration

Bound test for cointegration	F-statistics	t-statistics
Model 1	1.749	−1.67
Model 2	3.175	−1.056
Model 1: critical values	Lower bound, I(0)	Upper bound, I(1)
1% level of significance	6.34	7.52
5% level of significance	4.87	5.85
10% level of significance	4.19	5.06
Model 2: critical values	Lower bound, I(0)	Upper bound, I(1)
1% level of significance	5.17	6.36
5% level of significance	4.01	5.07
10% level of significance	3.47	4.45

** denotes 5% level of significance. The Schwarz Information Criterion was used to select the appropriate lags for each variable of both models. Source: Authors

Additionally, the 2006 structural break dummy variable (D_{2006}) is not statistically significant in the short term, suggesting that there was no rapid emissions shock in that year that could be explained by GDP and other factors.

Several important conclusions are shown by the long-run estimations. First, with an elasticity of 0.886, which is significant at the 1% level, GDP per capita (ln_GDP) shows a large positive impact on CO_2 emissions. This finding supports hypothesis H1 and indicates that Kazakhstan's economic growth is still mostly carbon-intensive, with no indication of a turning point in the Environmental Kuznets Curve (EKC) within the range that has been observed.

Higher urbanisation is linked to significant decreases in CO_2 emissions when GDP and other parameters are held constant, as evidenced by the enormous negative coefficient (−19.498, $P < 0.01$) that urbanisation (ln_URB) exhibits. This conclusion supports hypothesis H2, which states that urbanisation in Kazakhstan may help reduce emissions through increased efficiency and structural shifts towards less carbon-intensive activities, even though it goes against the initial expectation of a positive correlation.

Urbanisation and global uncertainty have a positive but non-statistically significant interaction term (ln_URB × ln_WUI)

Table 9: ARDL-ECM estimates - Model 1 (baseline)

Long-run				Short-run			
Variable	Coeff	t-stat	(Prob)	Variable	Coeff	t-stat	(Prob)
ln_GDP	0.886***	6.702	(0.000)	Δln_GDP	0.688**	2.826	(0.010)
ln_RWN	−0.016	−0.278	(0.783)	Δln_RWN	0.083	1.348	(0.191)
ln_WUI	0.011	1.280	(0.213)	Δln_WUI	0.003	0.502	(0.620)
ln_URB	−19.498***	−4.769	(0.000)	Δln_URB	−15.267	−0.850	(0.404)
Dummy 2006+	-	-	-	Dummy 2006+	0.004	0.156	(0.877)
				Constant	−1.820	−1.820	(0.075)
ECM_{t-1}	−0.812***	−4.526	(0.000)	R^2		0.626	
				Adj. R^2		0.529	

***P<0.01, **P<0.05. The long-run coefficients represent the estimated equilibrium impacts (α's). Short-run Δ terms represent immediate (1-year) effects. Source: Authors

Table 10: ARDL-ECM estimates - Model 2 (with interaction)

Long-run variable	Coefficient	t-statistic	(Prob)	Short-run Variable	Coefficient	t-statistic	(Prob)
ln_GDP	0.886***	6.702	(0.000)	Δln_GDP	0.687***	2.825	(0.010)
ln_RWN	−0.016	−0.279	(0.783)	Δln_RWN	0.083	1.348	(0.191)
ln_URB × ln_WUI	0.003	1.279	(0.213)	Δ(ln_URB × ln_WUI)	0.001	0.503	(0.620)
ln_URB	−19.494***	−4.769	(0.000)	Δln_URB	−15.259	−0.850	(0.404)
Dummy 2006+	—	—	—	Dummy 2006+	0.004	0.156	(0.877)
				Constant	−1.780	−1.780	(0.085)
ECM_{t-1}	−0.812***	−4.525	(0.000)	R^2		0.626	
				Adj. R^2		0.529	

***P<0.01, **P<0.05. The long-run coefficients represent the estimated equilibrium impacts (α's). Short-run Δ terms represent immediate (1-year) effects. Source: Authors

($P \approx 0.213$). This suggests that the relationship between urbanisation and emissions is not much moderated by global uncertainty, which means that hypothesis H4's moderation component is rejected.

The consumption of renewable energy (ln_RWN) shows a statistically insignificant yet negative influence on CO_2 emissions, indicating that the percentage of renewable energy is still too small to have a substantial impact on emission levels. Although this result shows the limited role of renewables thus far, it is consistent with hypothesis H3 in terms of the expected sign.

The direct impact of global uncertainty (ln_WUI) on emissions is negligible. All things considered, these findings show that domestic variables—GDP growth and urbanization—rather than outside uncertainties, dominate Kazakhstan's emissions trajectory.

Approximately 81% of any deviation from the long-run equilibrium is rectified within a year, according to the highly significant negative error-correction term (ECMt - 1) in both models (−0.812, $P < 0.01$). Despite the formal cointegration test's equivocal results, this strong adjustment speed supports the existence of a stable long-term link between the variables.

With an R^2 of roughly 0.63 and an Adjusted R^2 of roughly 0.53, the model has strong explanatory power. The absence of significant autocorrelation is confirmed by diagnostic tests such as the Durbin-Watson and Breusch-Godfrey tests, and the CUSUM stability test shows that the model stays stable throughout the sample period. Interestingly, adding the interaction component to Model 2 did not considerably increase the model's explanatory power, supporting the finding that Kazakhstan's emissions patterns are not substantially affected by global uncertainty.

This research contributes to the increasing range of literature on the environmental consequences triggered by the process of economic development and urbanisation in resource economies. Based on the Environmental Kuznets Curve (EKC) hypothesis (Grossman and Krueger, 1995; Stern, 2004) and the STIRPAT framework (Dietz and Rosa, 1994), the findings point to an observation of Kazakhstan in the upward-sloping portion of the EKC, where GDP continues to remain in a positive association with CO_2 emissions. Structural and technological transformation leading to the decoupling of growth from emissions, therefore, remains a work in progress.

Perhaps one of the most striking empirical findings is the long-term negative relationship between urbanisation and emissions, which challenges the notion that urban growth necessarily brings about environmental pressure (Jones, 2016; Ma and Ogata, 2023). In Kazakhstan, urbanisation seems to contribute to increased energy efficiency and modernization of infrastructure-an observation that is also consistent with STIRPAT in that the environmental impacts of population growth may be alleviated through technological and institutional improvement.

Therefore, this calls for a policy paradigm shift whereby cities must recommit to developing compact urban forms, public transportation infrastructure, and energy-efficient buildings. Such development strategies appear to be the best means whereby urban density advantages can be realized while simultaneously reducing environmental pressure in line with international climate commitments and national sustainable development goals.

The insignificance of the coefficient of renewable energy consumption to emissions further indicates underdeveloped implementation mechanisms. Although clean energy is at the forefront of Kazakhstan's strategic documents, its practical contribution to mitigating emissions is hardly noteworthy (Hasanov et al., 2019; Bhattacharya et al., 2017). This puts into perspective the urgency for institutional reforms, including:

- Strengthening independent regulatory bodies for energy oversight;
- Creating a conducive environment for green financing (e.g., subsidies, green bonds);
- Improving cross-sectoral collaboration to enable the mainstreaming of climate objectives into infrastructure, economic, and urban planning.

Such institutional reforms would thus enable the policy to be implemented in line with formal decarbonisation commitments and good international practice.

While global uncertainty, as measured by the World Uncertainty Index, is neither significantly affecting emissions nor its interaction with urbanisation, it remains a menace to the policy implementation process (Baker et al., 2016; Fu et al., 2022). Therefore, public administration must be adaptive in its governance. This consists of:

- Conducting scenario planning and risk-adjusted policy modelling;
- Building institutional flexibility to allow for immediate reallocation of resources during external shocks;
- Training of administrators in climate risk management and real-time policy evaluation.

Governance embodiment of such resilience will give great assurance that environmental programs remain in their tracks despite turbulent global conditions (Ayad et al., 2023).

In summary, the findings affirm that emissions in Kazakhstan are majorly driven by domestic economic growth, while urbanisation, when steered well by policymakers, could become a powerful engine for sustainability. Hence, bridging the gap between institutional ambition and implementation and infusing adaptive capacity into public administration stand out as the next forthwith steps toward Kazakhstan's low-carbon transition.

5. CONCLUSION

Kazakhstan is in the early stages of the Environmental Kuznets Curve (EKC), according to this study, and CO_2 emissions are still being driven by economic expansion. However, over time, urbanisation is linked to lower emissions, indicating either greater energy efficiency or a move away from high-emission industries in urban areas. This suggests that urbanisation with careful planning might be a useful tactic for sustainable growth.

Since renewable energy now makes up a very small portion of Kazakhstan's energy mix, its consumption is insignificant, which emphasises the need for more aggressive infrastructure and investment to scale up renewables. It was discovered that there was no discernible effect of global uncertainty on emissions, suggesting that domestic variables account for most Kazakhstan's emissions.

Decoupling growth from emissions, accomplishing climate targets, and raising living standards in Kazakhstan's cities and rural areas all depend on these measures.

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