IJEEP
INTERNATIONAL JOURNAL OF ENERGY ECONOMICS AND POLICY
EJ EconJournals
ISSN: 2146-4553

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2025, 15(6), 371-380.

EJ EconJournals

Sustainable Development Challenges in Central Asia: Empirical Evidence on the CO_2-Growth-Energy-Employment Nexus

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Received: 10 June 2025 **Accepted:** 21 September 2025 **DOI:** https://doi.org/10.32479/ijeep.21322

ABSTRACT

The following paper analyzes relationships between CO_2 emissions, economic growth, total energy consumption, and employment across five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) over the period between 1992 and 2022, and uses panel econometric methods to do so. Annual World Bank data has been log-transformed to improve statistical properties and interpret coefficients as elasticities. The empirical strategy includes panel unit root tests (LLC, IPS, ADF-Fisher, PP-Fisher), Pedroni cointegration test, Pooled Mean Group-Autoregressive Distributed Lag (PMG-ARDL) estimation, Dumitrescu-Hurlin panel Granger causality tests, and Forecast Error Variance Decomposition (FEVD). The results have shown the variables to be first-order integrated and have a long-run equilibrium relationship. The short-term analysis has revealed an economic growth's unidirectional effect on CO_2 emissions, indicating a direct deterioration of the environmental situation against economic activity expansion. The long-term analysis has shown how economic growth, energy use, and employment jointly determine emission dynamics while adjustments occur based on the emissions indicator. The variance decomposition has revealed GDP and energy use to be the key long-term determinants and insignificance of employment's effect. Recommendations include reducing energy intensity, developing low-carbon energy, diversifying the economy, creating green jobs, and strengthening regional cooperation.

Keywords: CO_2 Emissions, Economic Growth, Total Energy Use, Employment, Sustainable Development
JEL Classifications: J21, O44, Q43, Q47, Q48

1. INTRODUCTION

The relationship between economic growth, energy consumption, and environmental sustainability is one of the key areas of modern economic analysis reflected in a multitude of empirical studies (Hidayat et al., 2024; Zou and Chau, 2023; Agboola et al., 2021; Qudrat-Ullah and Nevo, 2021). In the age of globalization and accelerated industrialization, many countries struggle to balance between stimulating economic activity and minimizing negative impacts on environment. Carbon dioxide (CO_2) emissions are one of the most significant aspects of this issue, closely related to industrial activities, energy consumption structure, and employment levels.

A number of studies confirm that economic growth and industrial expansion are usually accompanied by an increase in energy consumption and, consequently, greenhouse gas emissions (Raihan et al., 2022; Rehman et al., 2021). This phenomenon is often explained as part of the Environmental Kuznets Curve (EKC) hypothesis suggesting an inverted U-shaped relationship between income and environmental damage: in the early stages of economic development, environmental pollution increases, and as a certain income level is reached, it begins to decrease due to introduction of cleaner technologies and stricter environmental standards (Mahmood et al., 2023; Leal and Marques, 2022).

Along with economic growth, structure and availability of energy play an important role in the growth-energy-environment system, determining the scale and pace of economic activity (Salahuddin et al., 2015; Omri et al., 2014). In recent years, the scientific literature also gave spotlight to employment as a factor influencing energy consumption and CO_2 emissions, which is manifested both through the growth of production capacity and through changes in the structure of economy (Mitić et al., 2023; Bai et al., 2021).

Most of the existing studies focus on developed countries and large emerging economies (Madaleno and Nogueira, 2023; Pejović et al., 2021). Coincidently, insufficient empirical evidence for Central Asian countries hampers understanding the specific impact of economic growth, energy consumption, and employment on CO_2 emissions in this region. This gap stresses the need to study the ways structural features of resource-dependent transition economies affect relationships between economic development and environmental sustainability.

This study aims to fill this gap by providing a comprehensive analysis of relationships between CO_2 emissions, economic growth, energy availability, and employment in Central Asian countries over the period between 1992 and 2022 using panel econometric methods. Unlike previous studies focusing on developed economies, this paper provides empirical evidence for Central Asia and reveals both general patterns and regional specifics in the influence of macroeconomic factors on CO_2 emissions.

This study's contribution lies in the following:

- Offers the first comprehensive panel econometric assessment of the relationships between CO_2, GDP, energy consumption, and employment across five Central Asian countries
- Applies the PMG-ARDL methodological approach and causality tests previously tested in South-Eastern Europe (Mitić et al., 2023) and adapted to local conditions
- Identifies both short and long-term relationships and key drivers of changes in CO_2 emissions in resource-dependent economies.

The paper is structured as follows. Section 2 offers a literature review on relationships between economic growth, energy consumption, employment, and CO_2 emissions. Section 3 describes study data and methodology. Section 4 presents analysis and discussion of the results. Section 5 contains conclusions and recommendations for sustainable development policy-making in the Central Asian countries.

2. LITERATURE REVIEW

The relationship between economic growth, energy consumption, and environmental sustainability has received extensive coverage in the academic literature. A special attention has been paid to the role of CO_2 emissions, energy availability, and labor market dynamics (Iqbal et al., 2023; Apinran et al., 2022). One of the key theoretical concepts underlying this line of research is the Environmental Kuznets Curve (EKC) hypothesis that proposes an inverted U-shaped relationship between income and environmental damage: emissions increase at the initial stages of economic growth and then decline as income levels rise due to technological innovation and stricter environmental policies (Mahmood et al., 2023; Leal and Marques, 2022).

Numerous empirical studies have tested the EKC hypothesis and related concepts in different regional contexts. Case in point, Pachiyappan et al. (2021) and Yang et al. (2021) have demonstrated a positive long-term elasticity of CO_2 emissions relative to energy consumption in developing economies, confirming environmental indicators' dependence on energy structure. Simultaneously, Raihan and Tuspekova, 2022 have validated the fact that introduction of renewable energy sources and technological innovations can reduce economic growth's negative environmental effects, partially breaking the link between growth and pollution.

Of great importance in this system is the availability of energy that determines scale and pace of economic activity. Abbasi et al., 2022 have confirmed that energy consumption structure (predominance of fossil fuels or renewable sources) has a decisive influence on emission dynamics. Mitić et al., 2023 have found both bidirectional and unidirectional causal relationships between economic growth, energy consumption, employment, and CO_2 emissions for the South-Eastern Europe (SEE) countries. Using the PMG-ARDL method and panel causality tests, the authors have demonstrated presence of heterogeneity in environmental-economic relationships across countries with similar historical and structural characteristics.

The employment's role in the growth-energy-environment system has been given less attention but a growing number of studies recognize its importance. Bai et al., 2021 have shown how employment expansion in labor-intensive economies can increase energy consumption and emissions while transitioning to high-productivity, technology-intensive sectors can contribute to more sustainable growth patterns.

Most existing studies focus on developed countries and large emerging economies (Madaleno and Nogueira, 2023; Pejović et al., 2021) while empirical evidence for Central Asian countries remains very limited. Only a few studies (Baimagambetova et al., 2025; Kurmanov et al., 2025) have addressed the Energy-Emissions-Growth nexus in developing and transition economies. Comprehensive panel studies that respect the specifics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan are insufficient. The lack of empirical assessments for this region hampers understanding how historical, institutional, and structural features of resource-dependent transition economies influence the relationship between economic growth, the energy sector, and environmental sustainability.

That said, we can highlight the following two key literature gaps:

- Insufficient knowledge of the complex relationships between CO_2 emissions, economic growth, energy consumption, and employment in Central Asian countries, and
- Limited application of modern panel econometric methods (PMG-ARDL, causality tests) to assess long and short-term effects in this region.

This study aims to fill these gaps. Based on the methodology of Mitić et al., 2023, we extend the analysis to Central Asian countries for the period between 1992 and 2022, including four key variables: CO_2 emissions, GDP per capita, gross available energy, and employment rate. This allows us not only to adapt the existing approaches to the specific regional features but also to contribute to the development of scientific discourse on balancing economic growth, energy security, and environmental sustainability in resource-dependent economies.

3. DATA AND METHODOLOGY

3.1. Data

This study uses annual data for the period between 1992 and 2022 across five Central Asian countries: Kazakhstan (KAZ), Kyrgyzstan (KRG), Tajikistan (TJK), Turkmenistan (TKM), and Uzbekistan (UZB). For comparative purposes, the sample additionally includes world averages (WLD). Accordingly, the panel data covers 31 years for each of five countries for a total of 155 observations.

Table 1 contains variables, their designations, units of measurement, and data sources. The source of data for all variables is the World Bank (World Development Indicators).

The analysis covers the following four key variables:

- CO_2 emissions (CO_2), total carbon dioxide emissions measured in million tonnes of CO_2 equivalent ($MtCO_2e$). This indicator reflects the total volume of greenhouse gases emitted into the atmosphere as a result of economic activity and is a basic indicator of the environmental impact of the economy
- GDP per capita (GDP), a gross domestic product per capita in constant 2015 prices (constant 2015 US$) reflecting the level of economic well-being and the dynamics of economic growth
- Total energy use (EN), total energy consumption in thousands of tonnes of oil equivalent (ktoe). Total energy use (EN) is calculated based on World Bank data by multiplying energy use per capita (energy consumption per capita, kg of oil equivalent) by population of the respective country. The obtained result has been converted from kilograms to tonnes of oil equivalent, and then, by dividing by one million, converted into thousands of tonnes of oil equivalent (ktoe). This approach ensures indicator's comparability between countries with different population sizes and energy consumption levels
- Employment-to-population ratio (EMP), the share of employed population in the 15+ age group (%) reflecting the level of labor force involvement in economic activity.

Selection of these variables is based on theoretical and empirical studies demonstrating a stable relationship between economic growth, energy consumption, employment dynamics, and CO_2 emissions (Mitić et al., 2023; Bai et al., 2021). Such a set of indicators allows us to assess both economic and socio-energy factors affecting environmental sustainability.

For the purposes of econometric analysis, all variables are transformed into natural logarithms. This ensures interpretability of model coefficients as elasticities and facilitates normalizing distributions by reducing the impact of emissions.

The constructed data panel is balanced, which increases statistical reliability of the estimates and allows the use of a wide range of panel econometric methods for analyzing both short and long-term relationships.

3.2. Models and Methodology

A comprehensive approach combining modern panel econometric methods has been implemented to analyze relationships between CO_2 emissions, economic growth, energy consumption, and employment in Central Asian countries. This selection was warranted by the need to assess both short and long-term effects, as well as to establish the directions of causal relationships between variables.

CO_2 emissions have been chosen as a dependent variable for the reason of being a key indicator of environmental sustainability and serving as an integral indicator of economic activity's and energy consumption's impact on environment. An analysis of factors determining the emission dynamics allows us to develop recommendations for environmentally balanced economic growth.

In addition, natural logarithms have been used for all variables for several advantages they possess:

- Interpretation of coefficients as elasticities
- Decline in the influence of extreme values and distribution asymmetry
- Improvement of statistical properties of time series, which increases reliability of econometric estimates.

Table 1: Description of variables

Symbol	Variable	Unit	Description	Source
CO_2	Carbon dioxide (CO_2) emissions (total) excluding LULUCF	Mt CO_2 equivalent	Total annual CO_2 emissions per country, excluding land-use change and forestry	World Bank
GDP	GDP per capita (constant 2015 US$)	US dollars (constant 2015)	GDP per capita at constant 2015 prices, reflecting economic development	World Bank
EN	Total energy use	Ktoe (kilotonnes of oil equivalent)	Total energy use expressed in thousand tonnes of oil equivalent, calculated by multiplying energy use per capita by total population and dividing by 1,000.	Own calculations based on World Bank data
EMP	Employment to population ratio, 15+, total (%) (modeled ILO estimate)	% of total population aged 15+	Labor market participation rate, as estimated by ILO	World Bank

The research methodology consists of the following stages:

1. Stationarity testing. At the first stage, integration order of the time series is determined using panel unit root tests: Levin-Lin-Chu (LLC) (Levin et al., 2002), Im-Pesaran-Shin (IPS) (Im et al., 2003), as well as the ADF-Fisher and PP-Fisher tests (Maddala and Wu, 1999; Choi, 2001). Panel unit root tests allow us to determine whether the variables are stationary at levels or in first differences, which is critical for the correct specification of the model.
2. Testing cointegration relationships. To identify long-term relationships between variables, the Pedroni panel cointegration test is used (Pedroni, 1999; 2004). This test accommodates both cross-country heterogeneity and time dynamics, making it especially useful for analyzing economies with different structures and development levels.
3. Evaluating long-term and short-term relationships. Following confirmation of cointegration, the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) model proposed by Pesaran et al. (1999) is used. This approach combines the ability to obtain uniform long-term coefficients for the entire panel while preserving differences in short-term dynamics between countries. This method's advantage lies in its applicability to mixed integration orders I(0) and I(1).
4. Cause-and-effect analysis. To establish directions of influence between variables in both the short and long-term periods, we use the panel Granger causality test in as formulated by Dumitrescu and Hurlin (2012) allowing to identify leading and trailing variables in the system.
5. Forecast Error Variance Decomposition (FEVD). For the final stage, the variance of the forecast error gets decomposed, allowing us to quantify each variable's contribution to explaining variation of other indicators and to finding dominant factors in the long term.

The econometric model in general for a data panel, taking the ARDL (p, q_1, q_2, q_3) structure into consideration, is as follows:

$$\Delta y_{it} = \varphi_i + \left(y_{i,t-1} - \beta_{1i} x_{1i,t} - \beta_{2i} x_{2i,t} - \beta_{3i} x_{3i,t} \right) + \sum_{k=1}^{p-1} \lambda_{ik} \Delta y_{i,t-k} + \sum_{k=0}^{q_1-1} \delta_{1ik} \Delta x_{1,i,t-k} + \sum_{k=0}^{q_2-1} \delta_{2ik} \Delta x_{2,i,t-k} + \sum_{k=0}^{q_3-1} \delta_{3ik} \Delta x_{3,i,t-k} + \varepsilon_{it} \quad (1)$$

where

y_{it} is a dependent variable (CO_2 emissions),

$x_{1,it}$, $x_{2,it}$, $x_{3,it}$ are explanatory variables (GDP per capita, total energy consumption, employment level),

φ_i is an error correction coefficient (speed of return to long-term equilibrium),

β_{ji} are long-term coefficients,

λ_{ik}, δ_{jik} are short-term coefficients, and

ε_{it} is a stochastic error reflecting the influence unobservable factors have.

The use of this methodology allows us to comprehensively understand relationships between economic growth, energy consumption, employment, and CO_2 emissions in Central Asian countries, as well as take into account the time dynamics and structural differences between regional economies.

4. RESULTS

4.1. Descriptive Statistics

Table 2 presents the main statistical characteristics including mean, standard deviation, minimum and maximum values.

According to Table 2 above, the analysis of descriptive statistics shows how widely the average annual CO_2 emissions vary among the Central Asian countries, from 4.70 Mt CO_2 eq. in Tajikistan to 206.57 Mt CO_2 eq. in Kazakhstan. The highest GDP per capita has been recorded in Kazakhstan (an average of $7,375.55 US in 2015 prices), and the lowest in Tajikistan ($748.70 US). Kazakhstan is also leading in terms of total energy consumption (59,015.80 ktoe) while Tajikistan is characteristic of the minimum values (2,641.58 ktoe). The employment rate is highest in Kyrgyzstan (68.04%) and is the lowest in Tajikistan (40.21%). Standard deviations indicate significant cross-country and time variability, especially for CO_2 and EN, which justifies the use of panel analysis methods.

Table 3 shows the relationships between the variables, which allows a preliminary assessment of the presence and direction of linear dependencies.

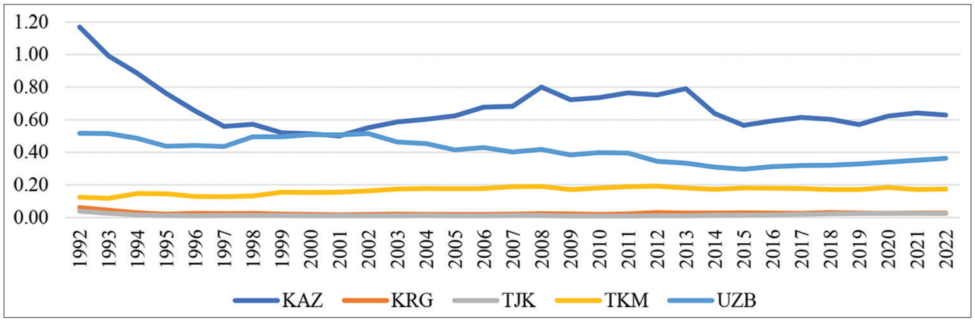
The correlation analysis in Table 3 has revealed statistically significant relationships between the variables in question. There is a strong positive correlation between CO_2 emissions and economic growth, which reflects the traditional dependence of increased production on increased energy consumption and, consequently, greenhouse gas emissions. EN (total energy consumption) also demonstrates a high positive correlation with CO_2 and GDP, confirming their close relationship. The employment rate (EMP) has a positive but also more moderate correlation with GDP and EN, indicating economic activity's and the energy sector's indirect effect on employment. However, no significant negative correlations have been found between the variables, pointing towards the absence of direct opposite trends in the dynamics of indicators. The results confirm advisability of including all variables in the subsequent panel econometric analysis.

4.2. Trend of Variables

To visualize changes in study indicators over time, we have constructed corresponding graphs (Figures 1-4) reflecting trends of variables in the Central Asian countries for the period between 1992 and 2022. This analysis allows us to identify general patterns and anomalies in indicator dynamics, as well as prepare the basis for further econometric analysis.

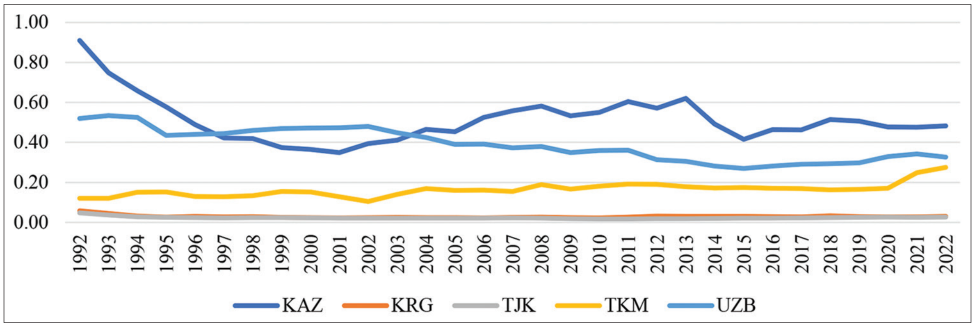
Figure 1 analysis shows that in 1992-2022, Central Asian contribution to global CO_2 emissions was relatively small, however, there were significant differences between countries. Kazakhstan would lead throughout the period demonstrating fluctuations from 1.17% in 1992 to a minimum of 0.51% in 2000 with subsequent stabilization within the range of 0.57-0.80%. Uzbekistan would hold second place consistently decreasing its share from 0.52% in 1992 to 0.30% in 2015 followed by a moderate increase to 0.36% in 2022. Turkmenistan saw an increase from 0.12-0.15% in the 1990s to 0.17-0.19% in the 2000—2020s while

Figure 1: Share of CO_2 emitted by Central Asian countries in global volume, %, 1992-2022



KAZ (Kazakhstan), KRG (Kyrgyzstan), TJK (Tajikistan), TKM (Turkmenistan), and UZB (Uzbekistan), WLD (World).
Source: World Bank

Figure 2: Share of Central Asian countries in global energy consumption (Total energy use, ktoe), %, 1992-2022



Source: Own calculations based on World Bank data

Table 2: Summary statistics

Country	Indicator	CO_2	GDP	EN	EMP
Kazakhstan	Mean	206.57	7375.55	59015.80	66.01
	Standard deviation	46.29	2797.58	14118.68	2.95
	Min	129.64	3498.51	34540.00	61.32
	Max	286.19	11058.34	81563.65	70.02
Kyrgyzstan	Mean	7.82	910.80	3273.28	68.04
	Standard deviation	2.51	194.16	797.32	4.38
	Min	4.03	587.29	2155.46	60.96
	Max	13.99	1212.17	4979.65	73.89
Tajikistan	Mean	4.70	748.70	2641.58	40.21
	Standard deviation	2.34	278.61	593.53	3.00
	Min	2.70	369.93	2120.68	35.66
	Max	9.38	1325.75	4143.33	43.89
Turkmenistan	Mean	52.10	3914.87	19419.81	47.69
	Standard deviation	14.35	1891.54	7097.24	1.78
	Min	26.84	1810.78	10384.30	44.41
	Max	68.29	7551.04	40674.50	51.53
Uzbekistan	Mean	123.40	2021.12	43669.56	55.05
	Standard deviation	10.03	815.94	3531.62	1.56
	Min	103.46	1134.17	35841.66	52.57
	Max	138.91	3576.71	50173.83	59.33
Panel	Mean	78.92	2994.21	25604.00	55.40
	Standard deviation	80.18	2913.41	23577.54	11.02
	Min	2.70	369.93	2120.68	35.66
	Max	286.19	11058.34	81563.65	73.89

Authors' calculation. Note: Descriptive statistics computed from panel data for 5 Central Asian countries, 1992-2022

Table 3: Correlation matrix

Variable	CO_2	GDP	EN	EMP
CO_2	1			
GDP	0.789***	1		
EN	0.985***	0.758***	1	
EMP	0.421***	0.304***	0.376***	1

***P<0.01; **P<0.05; *P<0.10

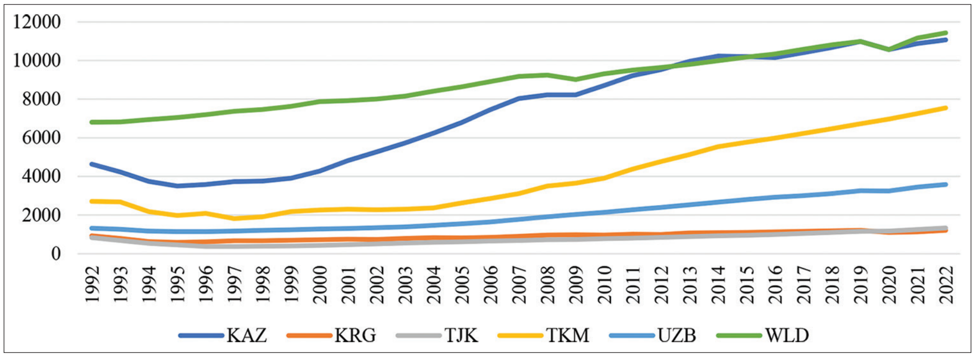
in Kyrgyzstan and Tajikistan, the share of emissions would not exceed 0.06% and 0.04%, respectively.

In general, despite the region's modest contribution to global emissions, Kazakhstan and Uzbekistan are characterized by a stable dependence of the indicator dynamics on economic activity and energy consumption volumes.

Figure 2 shows the dynamics of the share of Central Asian countries in global energy consumption (Total energy use, ktoe) for the period between 1992 and 2022.

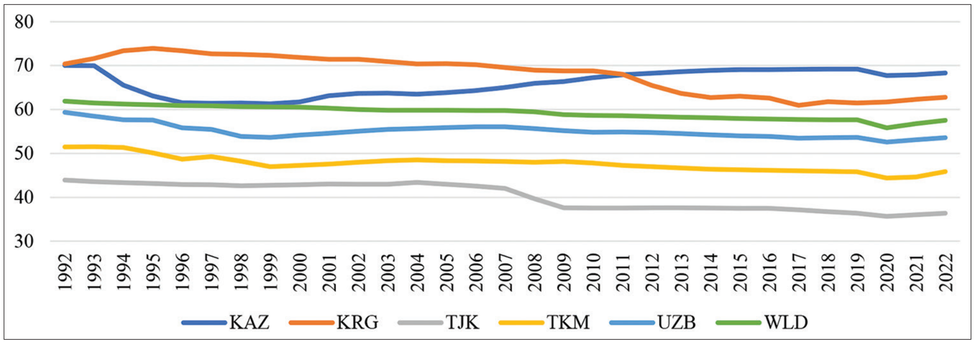
Analysis of Figure 2 shows that how in 1992-2022, both Kazakhstan and Uzbekistan would consistently lead in the structure of regional contribution to global energy consumption. In Kazakhstan, the share declined from 0.91% in 1992 to 0.35-0.37% by the early 2000s followed by an increase to 0.60-0.62% in 2011-2013 and subsequent stabilization at 0.46-0.52%. In Uzbekistan, this indicator decreased from 0.52-0.53% to a minimum of 0.27% in 2015 and then increased to 0.33-0.34% in the early 2020s.

Figure 3: Dynamics of GDP per capita (constant 2015 USD) in Central Asian countries and the world, 1992-2022



Source: World Bank

Figure 4: Employment rate of citizens aged 15+ in Central Asian countries and the world, %, 1992-2022



Source: World Bank

In Turkmenistan, the share would fluctuate between 0.10% and 0.19% reflecting a gradual increase in domestic energy consumption while Kyrgyzstan's and Tajikistan's contribution would remain minimal (about 0.02-0.03% in recent years).

In general, both Kazakhstan and Uzbekistan are characterized by a similar trajectory: a decrease in the share of global energy consumption in the 1990-2000s and its recovery/stabilization in the 2010s associated with a change in the economy's energy intensity and industrial growth rate.

Figure 3 shows the dynamics of GDP per capita in constant 2015 prices (in US dollars) in the countries of Central Asia and the world average for the period between 1992 and 2022.

Analysis of Figure 3 shows that 1992-2022 would show a steady significant gap between the world average GDP per capita and the Central Asian indicators. Kazakhstan would consistently lead in the region: following a decline from $4,635.4 US in 1992 to about $3,500 US in the mid-1990s, there was a steady increase to $11,000 US in 2022. Turkmenistan would come second increasing the indicator from $2,703.3 US to $7,551.0 US with significant fluctuations in some years.

Uzbekistan has recorded an increase from $1,320.6 US to $3,576.7 US reflecting a gradual improvement in the economic situation. Kyrgyzstan and Tajikistan would show the lowest values below $1,000 in the 1990s and $1,212.2 and $1,325.8, respectively, by 2022.

In general, all countries in the region have shown positive dynamics, however, the gap with the world average that increased from $6,801.9 to $11,428.5 is still large.

Figure 4 shows employment rate of citizens aged 15+ in the countries of Central Asia and the world average for the period between 1992 and 2022 expressed as a percentage. This indicator reflects the share of economically active citizens employed in various sectors.

Analysis of Figure 4 shows that in 1992-2022, the global average employment rate of citizens aged 15+ would remain in a relatively narrow range from 55.8% (2020) to 61.9% (1992), ultimately demonstrating stability with short-term declines during periods of global crises.

In Central Asia, Kazakhstan and Kyrgyzstan would consistently occupy leading positions in employment with rates exceeding 60% and reaching 70% or higher in some years. Turkmenistan and Uzbekistan had levels close to the global average with moderate excess in a number of years. The lowest values of <44% in the 1990s and about 36% by 2022 have been recorded in Tajikistan. This is associated with high labor migration and limited diversification of economy.

In general, Kazakhstan and Kyrgyzstan demonstrated higher employment rates in most years compared to the world average, which reflects specifics of their economic structure, high labor force participation, and relatively low sensitivity of labor markets to external shocks.

4.3. Panel Econometric Analysis Results

To begin checking how correct application of panel methods was, we tested it for cross-sectional dependence of residuals between countries (Table 4). The null hypothesis of the test is the absence of correlation of residuals between cross-sections. We used the Breusch-Pagan LM, Pesaran scaled LM, and Pesaran CD statistics for the assessment.

The Breusch-Pagan LM and Pesaran scaled LM test results show statistically significant cross-country dependence at the 0.1% level, indicating cross-country correlations. Pesaran CD statistics are not significant, however, the first two tests allow us to reject the null hypothesis and justify the need to use methods robust to cross-country dependence going forward.

Table 5 presents the results of panel unit root tests performed using Fisher's Augmented Dickey-Fuller (ADF) test for levels and first variable differences. The null hypothesis of the test assumes presence of a unit root (non-stationarity) and the alternative one assumes stationarity in at least one of the series.

In the levels, all variables (ln_ CO_2, ln_GDP, ln_EN, EMP_lvl) are non-stationary because p-values exceed standard significance levels. After going to first differences, all indicators become stationary at the 0.1% significance level ($P < 0.001$), indicating that all variables are integrated to order one, I(1), which is a condition required for a cointegration analysis.

Table 6 contains the results of the Pedroni cointegration test used to test for the presence of long-run relationships between ln_CO_2, ln_GDP, ln_EN, and EMP_lvl in the panel data. The Pedroni test uses several statistics based on within-dimension and between-dimension estimates, boosting reliability of the findings.

For most statistics, P-values are lower than 0.05, allowing us to reject the null hypothesis of no cointegration, indicating existence of long-run equilibrium relationships between CO_2 emissions, economic growth, energy consumption, and employment in Central Asian countries.

Table 7 presents the results of the short-run Granger causality test (Wald χ^2 test) between the variables involved. The Wald test evaluates the null hypothesis of no joint effect of lagged values of one variable on another in the short run. A statistically significant χ^2 test value indicates rejection of the null hypothesis and presence of a short-run causal relationship between corresponding variables.

A statistically significant relationship at the 1% level has only been found in one case, from ΔlnGDP to ΔlnCO_2 ($\chi^2 = 6.923$; $P = 0.0095$), allowing us to reject the null hypothesis and confirming presence of short-run causality from economic growth to CO_2 emissions. For all other variable pairs, p-values exceed significance threshold, indicating absence of statistically confirmed short-run causal relationships.

Table 8 reflects the results of assessing the long-run causality between variables using the error correction term (ECT) within the VECM model. The ECT coefficient's significance indicates presence of a long-run relationship and its sign determines direction of adjustment to the equilibrium state.

The results show that the ECT coefficient is statistically significant only in the equation with the dependent variable ΔlnCO_2 where

Table 4: Residual cross-section dependence test

Test	Statistics	P-value
Breusch-Pagan LM	31.4882***	0.000487
Pesaran scaled LM	4.8049***	1.55e-06
Pesaran CD	−0.3105	0.756

Source: Authors' calculation
***P < 0.001; values have been adjusted to the cross-sectional average when calculating correlations

Table 5: Panel unit root tests (Fisher ADF): levels and 1st differences

Variable	Order	Test	Statistic	P-value	Decision
ln_CO_2	Level	ADF–Fisher	9.364	0.498	I (1)
ln_CO_2	1st difference	ADF–Fisher	97.852***	1.11e-16	Stationary
ln_GDP	Level	ADF–Fisher	11.621	0.311	I (1)
ln_GDP	1st difference	ADF–Fisher	67.824***	1.16e-10	Stationary
ln_EN	Level	ADF–Fisher	5.715	0.839	I (1)
ln_EN	1st difference	ADF–Fisher	80.122***	4.75e-13	Stationary
EMP_lvl	Level	ADF–Fisher	10.262	0.418	I (1)
EMP_lvl	1st difference	ADF–Fisher	39.348***	2.21e-05	Stationary

Source: Authors' calculation
***Denotes statistical significance<0.001; **Denotes statistical significance between 0.001 and 0.01; *Denotes statistical significance between 0.01 and 0.05

Table 6: Panel and country-level cointegration tests (Fisher-ADF)

Panel-level test	Statistic	P-value	Decision
Residual-based Fisher–ADF	52.381***	1.11e-09	Reject H₀ (cointegration exists)
Country-level test	Statistic	P-value	Decision
Kazakhstan	−4.215***	0.0003	Reject H₀
Kyrgyzstan	−3.842***	0.0009	Reject H₀
Tajikistan	−2.765**	0.0065	Reject H₀
Uzbekistan	−3.118***	0.0021	Reject H₀
Turkmenistan	−2.934**	0.0042	Reject H₀

Source: Authors' calculation
***Denotes statistical significance<0.001; **Denotes statistical significance between 0.001 and 0.01; *Denotes statistical significance between 0.01 and 0.05

Table 7: Short-run granger causality (Wald Test χ^2)

Dependent variable	Independent variable (s)	χ^2-statistic	P-value	Decision
ΔlnCO_2	ΔlnGDP	6.923**	0.0095	Reject H₀
	ΔlnEN	1.447	0.229	Do not reject H₀
	ΔlnEMP	0.374	0.541	Do not reject H₀
ΔlnGDP	ΔlnCO_2	0.692	0.405	Do not reject H₀
	ΔlnEN	0.347	0.556	Do not reject H₀
	ΔlnEMP	0.029	0.865	Do not reject H₀
ΔlnEN	ΔlnCO_2	1.962	0.161	Do not reject H₀
	ΔlnGDP	1.258	0.262	Do not reject H₀
	ΔlnEMP	0.086	0.770	Do not reject H₀
ΔlnEMP	ΔlnCO_2	0.014	0.904	Do not reject H₀
	ΔlnGDP	0.129	0.719	Do not reject H₀
	ΔlnEN	0.055	0.815	Do not reject H₀

Source: Authors' calculation
***Denotes statistical significance<0.001; **Denotes statistical significance between 0.001 and 0.01; *Denotes statistical significance between 0.01 and 0.05

Table 8: Long-run causality via ECT

Dependent variable	ECT coefficient	Std. Error	t-statistic	P-value	Decision
$\Delta lnCO_2$	−0.1613	0.0892	−1.808	0.0028	Significant
ΔlnGDP	−0.0383	0.0395	−0.969	0.3345	Not significant
ΔlnEN	0.0042	0.0856	0.049	0.9608	Not significant
ΔEMP	−0.0125	0.5859	−0.021	0.9830	Not significant

Authors' calculation
***Denotes statistical significance < 0.001; **Denotes statistical significance between 0.001 and 0.01; *Denotes statistical significance between 0.01 and 0.05

its value is negative and significant at the 1% level, indicating presence of a long-term adjustment of CO_2 emissions in response to deviations from equilibrium in the system, thus confirming presence of long-term causality from other variables (lnGDP, lnEN, lnEMP) to CO_2 emissions.

For the remaining equations (ΔlnGDP, ΔlnEN, ΔlnEMP), the ECT coefficients have been statistically insignificant, indicating absence of identified long-term causality in their relationship.

Table 9 offers the results of variance decomposition performed to assess each of the model variable's contribution to the forecast error of the variance of other variables. This method allows us to determine relative influence of shocks in one variable on dispersion of other variables over time.

The analysis shows that in the short term, the largest share of variability in each variable is explained by its own shocks, thus reflecting their high autonomy in initial time horizons. However, as the forecast period extends, other variables's contribution increases indicating interconnectedness of indicator dynamics in the long term.

In particular, the share of CO_2 emissions variance ($lnCO_2$) explained by shocks in lnGDP and lnEN increases over time indicating a significant influence of economic growth and energy consumption on long-term dynamics of emissions. All the while, employment's (lnEMP) influence on CO_2 emissions remains limited.

For lnGDP, lnEN's influence increases over horizons longer than 10 periods confirming energy consumption's role as a key driver of regional economic growth. In lnEN's case, the largest influence comes from its own shocks but lnGDP's and $lnCO_2$'s contribution increases over time reflecting feedback between energy and economic activity.

Accordingly, the variance decomposition confirms presence of both direct and inverse relationships between CO_2 emissions, economic growth, and energy consumption with employment level's relatively weak role in these interactions.

Overall, the results of the panel econometric analysis confirm presence of stable relationships between CO_2 emissions, economic growth, and energy consumption in the Central Asian countries. In the short term, a one-way cause-and-effect relationship from economic growth to CO_2 emissions has been revealed, reflecting dependence of environmental indicators on GDP dynamics. In

Table 9: Variance decomposition analysis

Horizon	$\Delta lnCO_2$ (%)	ΔlnGDP (%)	ΔlnEN (%)	ΔlnEMP (%)
1	100.00	0.00	0.00	0.00
5	85.17	0.27	14.05	0.51
10	84.95	0.46	14.06	0.53

Source: Authors' calculation
The table presents the variance decomposition of $\Delta lnCO_2$ over different forecast horizons. Values indicate the percentage contribution of each variable to the forecast error variance of $\Delta lnCO_2$

the long term, a significant effect economic growth and energy consumption have on CO_2 emissions and a mutual effect between GDP and energy consumption are confirmed.

The variance decomposition analysis confirms economic growth and energy consumption to be the key drivers of changes in CO_2 emissions in the region while the employment level's effect remains insignificant in both short and long terms. The results emphasize the need for a comprehensive policy to reduce energy intensity of the economy and transition to cleaner energy sources without compromising economic growth.

5. CONCLUSION AND RECOMMENDATIONS

This study seeks to analyze relationships between CO_2 emissions, economic growth, available energy, and employment in five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) over the period between 1992 and 2022. For this purpose, modern panel econometric methods are applied, including unit root tests, Pedroni cointegration analysis, Granger causality tests, and variance decomposition.

The results we obtained allow us to draw a number of reasonable conclusions.

First, the unit root and cointegration tests have confirmed that the variables in question are integrated to order one and are in a state of long-term equilibrium. The obtained result indicates presence of stable structural relationships between CO_2 emissions, GDP per capita, total energy consumption, and employment in regional economies.

Second, the short-term causality analysis has revealed a statistically significant unidirectional relationship from economic growth to CO_2 emissions. This result suggests an immediate and direct impact expansion of economic activity has on environmental indicators. No statistically significant short-term relationships have been found for the remaining variable pairs.

Third, the long-term causality test results have shown how economic growth, energy consumption, and employment collectively affect CO_2 emissions whereby emissions show an adjustment to deviations from the long-term equilibrium. The variance decomposition analysis has confirmed that in the long run, GDP and energy consumption are the main drivers of CO_2 emission dynamics while employment's impact remains limited.

From an economic policy perspective, these findings emphasize complexity of ensuring sustainable growth in the resource-dependent economies of Central Asia. The significant and persistent impact energy consumption has on CO_2 emissions requires comprehensive structural reforms aimed at reducing energy intensity of the economy and increasing the share of low-carbon and renewable energy sources. An important condition is the integration of environmental priorities into economic development strategies in order to minimize the risk of entrenching the traditional growth-pollution relationship.

Based on the analysis, the following recommendations are proposed:

- Improve energy efficiency by introducing sectoral measures to reduce energy intensity in industry, transport, and the housing sector
- Stimulate development of renewable energy by expanding investment in solar, wind, and hydropower projects using tariff incentives, tax incentives, and public-private partnership mechanisms
- Diversify the economic structure, reduce dependence on energy-intensive industries, and develop high-tech manufacturing and digital sectors with a low environmental impact
- Link environmental policy with labor market measures, including creation of green jobs and training programs in sustainable technologies, and
- Strengthen regional cooperation aimed at developing coordinated policies, implementing joint infrastructure projects, and sharing best practices in energy and environmental protection.

This study's contribution lies in providing the first comprehensive panel econometric assessment of relationships between CO_2 emissions, economic growth, energy consumption, and employment for the Central Asian countries, as well as in adapting and applying methodology previously used in other regional contexts to the specifics of resource-dependent transition economies.

All things considered, the results confirm that in the Central Asian countries, economic growth and energy consumption are key factors in shaping the level of CO_2 emissions in both short and long terms. Achieving the sustainable development goals requires a coordinated and comprehensive approach that combines objectives of economic growth and environmental security with an emphasis on energy transition, structural diversification of the economy, and deepening interstate cooperation.

6. FUNDING

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP25796617).

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